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The cumulus cloud investigations made by the Meteorological Research Flight during the period August 4th - 15th, 1952.

by
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Summary

The results of eight flights made to investigate the structure and environment of selected cumuliform clouds are presented. Details are given of the aircraft's instrumentation for this work and of the techniques used.

The flights reported were arranged, as far as possible, to coincide with other cumuliform cloud investigations made by the Department of Meteorology, Imperial College.

1. Introduction. At the request of the Department of Meteorology, Imperial College, the Meteorological Research Flight participated in an investigation of cumulus type clouds during the period August 4th - 15th, 1952.

It was agreed that as far as possible, during this period, the Meteorological Research Flight would make at least one flight a day in the region of Cranfield, the location of Imperial College's experiments which were termed "Project Cumulus".

On most days a detailed sounding of temperature and humidity up to cloud tops was made in a Hastings aircraft and was continued with an investigation of the structure of a selected cloud and its immediate environment. As far as possible measurements were made within the cloud, at several levels, of temperature, water content, icing rate, vertical motions and turbulence, and samples were taken of water droplets and ice crystals. Observations were then continued below cloud base with traverses at regular height intervals to near the surface in which measurements of temperature, humidity fluctuations and turbulence were made. Photographs were taken of interesting cloud features.

Concurrently with the Meteorological Research Flight measurements, the Imperial College contingent, with the co-operation of the Surrey Gliding Club and some R.A.F. personnel from R.A.E. Farnborough operated a two seat sailplane and a network of ground observing stations. Occasionally an Anson aircraft from the Cambridge University Air Squadron co-operated in the experiments. Unfortunately congestion of the available radio channels

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made it impossible for the measurements made by the Meteorological Research Flight to be closely co-ordinated with those made by the other participants and the investigations while simultaneous were in fact made entirely separately. One of the difficulties in this work was the necessity of avoiding Air Ways and maintaining quadrantal heights during the cloud flying. Throughout all these flights continuous contact was maintained with the Meteorological Radar Station at East Hill.

These eight flights were also made as part of a long series of cumulus and other cloud investigation flights by the Meteorological Research Flight and this is therefore an interim report which has been produced at this stage to make these observations available at the same time as those of the Imperial College team. The first objective of the longer series of flights is also to produce and present measurements made in this country of the main cloud parameters as this is necessary before any checks can be made on the large amount of theoretical work that has been done on this subject.

2. Aircraft Instrumentation.

(a) Temperature measurements were made using the standard Meteorological Office flat plate resistance thermometer with a balanced bridge.

The readings made with this instrument must be corrected for kinetic or frictional heating and, when in cloud, for wetting of the element. The former correction may be made accurately in clear air but the magnitude of the correction when the element is wet is somewhat doubtful. Recent American work indicated that the dry air correction should be reduced in the ratio saturated adiabatic lapse rate to dry adiabatic lapse rate and this is the procedure that has been adopted. Little confidence may be placed in the temperatures recorded immediately after leaving cloud since there is an undetermined wet bulb effect operative until the bulb of the thermometer has dried, a process normally taking about 30 seconds.

The lag of the thermometer is of the order of 8 seconds and the accuracy of the temperature readings about $\pm 0{\cdot}2^{\circ}F$ in clear air. In and after leaving cloud there may be errors of about $1^{\circ}F$.

(b) Humidity measurements were made using a manually operated Dobson-Brewer Frost Point Hygrometer.

There are no corrections to be made but the instrument is slow to operate above frost points of about $0^{\circ}F$. A skilled observer may make readings once or twice a minute to an accuracy of about $1^{\circ}F$ but below $-50^{\circ}F$ the speed of operating drops to about once every two minutes and the accuracy $2\text{-}3^{\circ}F$.

(c) Icing rate was measured using a rotating disc icing meter. A disc about 4 cm. in diameter and 2 mm. thick rotating at 2 r.p.m. is exposed to the airstream. Bearing on the edge is a probe which is mechanically connected to a transducer. Deflection of the probe by ice accumulated on the edge varies an air gap and thus an inductance in a previously balanced a.c. bridge circuit. Out of balance current is rectified and displayed on a meter as amount of ice per unit volume swept out by the disc.

The instrument is calibrated by exposure to standard conditions in an icing wind tunnel and its readings then converted to cloud water content. Small errors arise out of the departures of the density of the ice collected from that obtaining in the tunnel and out of inaccuracies in the standardisation of the tunnel. In addition the readings are only comparable when the cloud is purely supercooled water droplets. However, until recently, the cloud water contents measured with this

/instrument

instrument were always considered to be within say ±20% accuracy. Recent work, however, by Ludlam [1] in this country and by members of the N.R.C. Canada [2] has demonstrated that the instrument fails completely to give correct water contents when the actual cloud water content is greater than about 2 gm/cu. metre within the usual aircraft icing temperature range.

(d) Water content was also measured by means of a heated cylinder water content meter. It comprises two cylinders about a centimetre long and 0.3 cm. in diameter. One cylinder is exposed to the cloud droplets and the other is shielded from them in such a manner that both are under the same conditions of air flow.

The cylinders are wound with temperature sensing elements which form two arms of a Wheatstone bridge network. This is balanced in clear air in order to compensate for minor differences between the cylinders. Out of balance current, when in cloud, resulting from expenditure of power in the evaporation of intercepted droplets is recorded as water content of unit volume of air swept out by the cylinders.

Errors of the instrument arise mainly out of the calibration in the icing tunnel which is performed at the same time as that of the rotating disc icing meter. Accuracy is lowest at low water contents. In general the error is probably about ±10% - 15%. Lag is about 10 seconds.

(e) Turbulence was estimated subjectively every 10 seconds on a scale of 0.1 - 1.0g which has previously proved quite accurate for experienced observers. An accelerometer was also available but rarely used as very little extra information on bumpiness would have been provided by its use.

(f) Water droplets were sampled by both the Mazur type impactor and a recently developed pneumatically operated multi-shot impactor. In the former a magnesium oxide coated microscope slide, carried in a carefully designed housing, is exposed to the airflow for about a hundredth of a second by a simple shutter system. Intercepted droplets make craters in the coating whose size bear a known relation to the size of the droplets making them. The slide is viewed under a microscope and counts are made. Errors arise in the derived size distributions when the integrated area of the craters exceeds a certain fraction of the exposed area. An additional but small error is due to the low collection efficiency of the impactor for drops of diameter less than about 5.0 μ.

The pneumatic impactor has five slides which are carried on pistons. Operation of a valve pushes the slide out into the airflow after which it returns under the action of a spring; the time of exposure depends on the operation of the valve and at present is not accurately timed. The slides are coated with a heavy oil-Spirex 230-possessing desirable viscosity characteristics and in which the intercepted droplets lie unmodified. After exposure the slides are microphotographed in the aircraft. Errors are similar to those inherent in the Mazur method but efficiency of catch for smaller droplets is higher.

(g) Ice crystals are sampled by the Schaefer replica method. A microscope slide cooled to a sub-freezing temperature and coated with a 5% solution of Formvar 15-95 in ethylene dichloride is exposed to the decelerated airstream. Ice crystals falling on the slide form a transparent plastic skin round themselves and a hollow replica of the crystal is left attached to the slide. The replicas are viewed under a microscope by dark ground illumination. The only probable errors which may occur are due to shattering of the crystals on collection but care has been taken to prevent this occurrence as far as possible. Typical examples are shown in Figs. 20 a-i.

/(h)

(h) Vertical motions in cloud are derived from a record of the aircraft's height and airspeed. For all traverses the pilot was instructed to fly the aircraft as far as possible with constant power and elevator settings. Should the speed and height then increase together the aircraft must be in an updraught whose minimum strength recorded over the time lapse since the last reading is given by the displacement. Similarly mean minimum downdraught strength may be obtained. Accurate assessments of mean draught strengths may only be obtained when there is a height displacement at constant airspeed. Any change in height in antiphase with a change in airspeed is interpreted as caused by a control movement on the part of the pilot.

(i) The temperature field below and around cumulus clouds can be examined in great detail by means of the Ultra Rapid Thermometer described in M.R.P. 658?

Rapid variations in the wind field are similarly examined by means of hot wire anemometer apparatus using similar circuit arrangements. By means of a single hot wire rapid variations in total wind are recorded and, by means of a differential head, vertical components can be studied.

Very few records were obtained with this apparatus during these particular flights due to various instrumental faults but separate reports are in preparation both on the instruments themselves and recent studies made with them on the detailed wind and temperature field in which cumulus clouds are found.

3. Operational Procedure. After take-off the aircraft normally climbed to about 5,000 feet on track for Cranfield. When at this height instrument tests and calibrations were made.

The pilot then established communication with both East Hill Radar Station and Cranfield Control and the aircraft was identified and accepted for surveillance by the former.

At Cranfield the aircraft descended to 1,000 feet ICAN and commenced a temperature and humidity sounding, observations being made normally at 500 feet vertical intervals and continued well above the tops of any convective cloud in the area.

During the climb the pilot obtained information from Cranfield Control about the conduct of the ground experiment and determined the area in which the ground organisation was most interested. The radio channels however were invariably too congested to allow any close co-operation.

At the conclusion of the sounding the aircraft took up position over a selected cloud usually a large growing cumulus and made traverses in clear air above it and then through it, usually at five heights intermediate between tops and bases.

On reaching cloud base observations with the hot wire anemometers and ultra rapid thermometer were commenced. Usually at least three clear air traverses were made with each instrument serviceable, one being used at each height in succession before selecting the next.

At the completion of the investigation the aircraft returned to base, minor investigations being undertaken whilst on track.

4. Treatment of Results. In paragraphs below each flight is described in detail under three main headings:-

(i) The execution of the flight.

(ii) The soundings and their relation to the cloud features observed.

(iii) The results of the traverses.

/Photographs

Photographs of the clouds and also microphotographs of the cloud droplets and crystals are given in some cases.

It is not possible to describe all the cross section runs in detail within the compass of a short report so sub-para. (iii) has been usually divided into five sections (a) cloud structure (b) composition (c) vertical currents and turbulence (d) icing and water contents and (e) field below the cloud. In each case only a short description has been given. Full details have been tabulated but owing to their volume have not been attached to this report. In the more interesting cases, however, abridged tables of the main cloud features and tables and diagrams of the droplet and crystal distribution have been included.

Summary of Observations

Flights 1, 2, 3, and 8 were made in large cumulus or cumulonimbus clouds and the remainder in small cumulus or stratocumulus clouds.

When there were cumulonimbus clouds in the area the soundings were made up to about 22,000 feet usually although this was not as high as some of the cloud tops. Above this height the rate of climb of the Hastings aircraft becomes very slow. On the other occasions the soundings were made to 10,000 feet which was well above the cloud tops.

(i) The soundings and their relation to observed cloud features

(a) The height of the cloud base was generally in good agreement with that expected from the "parcel" method used in conjunction with the sounding. The height of cloud tops could not be estimated with the same accuracy by this method, although the main features were apparent e.g. it was quite obvious from each sounding whether it was a cumulonimbus or a small cumulus occasion. However, from a practical point of view the difficulty of forecasting the various cumulus parameters appears to be mainly a question of forecasting the sounding rather than a question of whether the parcel, slice, or similar methods are adequate to determine the amount of cumulus development. Although they are not reproduced here, the nearest radio sonde ascents were compared with the aircraft ascents and large differences were noted at times. These were, no doubt, due mainly to differences in space and time of the two soundings combined with developments of the synoptic situation. It appears from the aircraft soundings and cloud observations that a variation of 1°F in the ambient temperature at any level is enough to determine whether the cloud top shall be at that level or several thousand feet higher and the distribution of the tops of the smallest clouds seemed to be determined by "stops" of this magnitude. Similar differences will also determine whether there will be layers of stratocumulus or altocumulus mixed in with the cumuliform cloud at given levels. Hence a forecast of the sounding to this accuracy appears to be necessary before the detailed cloud forecast can be given.

(b) Although it appears inevitable from the water content measurements that entrainment must be an important factor in cumulus development several cases were noted of large cumulus clouds ascending through a comparatively dry environment. Any large scale mixing should then have destroyed the cloud tops. Our present view of entrainment from these and other flights is that it is a factor of considerable importance near the base and perhaps for the lower half of a large cumulus cloud but that at higher levels its magnitude decreases considerably.

(c) The tops of stratocumulus layers were usually determined by a decrease in the lapse rate or inversion, combined with a decrease in humidity. The bases were often not related to any obvious feature in the sounding although wind shear may have been the most important factor in these cases.

/(ii)

(ii) Cloud structure

(a) The large cumulus or cumulonimbus clouds investigated had lateral dimensions of about 10 miles at their middle levels. Lower down they often became larger with small cumulus clouds alongside them and at greater heights decreased in extent. Thin stratocumulus layers sometimes of lenticular form were often observed at various levels between the cumulus clouds. The large cumulus clouds all consisted of several cells in different stages of maturity and the individual cells varied in extent from one to four miles. The state of maturity of the different cells was often very obvious e.g. in the tops of a cumulonimbus one cell was glaciated while another contained considerable supercooled water. On other occasions some cells produced precipitation whilst adjacent cells did not do so and the direction of the vertical currents changed between and across the cells. Cloudy but relatively inactive regions up to a mile across were sometimes noted between the cells. The younger cells were usually downwind of the more mature cells.

(b) The small cumulus clouds usually had only one cell and were one to two miles across.

(iii) Cloud composition

(a) In the layer clouds ice crystal samples were taken at temperatures between -9°F and freezing point. On Flight No. 3 samples were also taken in altostratus cloud at about 20,000 feet. In Fli ht No. 8 no ice crystals were found down to temperatures as low as +6° F at 17,000 feet although it appeared later that glaciation of the cloud tops started soon after this observation was made.

The nature of the crystal distributions was very confused and details are given in the Tables relating to the individual flights. Dendritic types were rare and it appears that this type must be confined to a very narrow temperature band. Single hexagonal and tetragonal plates were most common with a few columns. Both the individual crystals and the aggregates appeared to decrease in size towards the top of the clouds.

Both snow (between 22°F and 28°F) and hail (at 22°F) were reported in Flight No. 3 only. Precipitation static was observed between temperatures of + 12°F and +23°F in a mixed cloud in Flight No. 1 and also reported at +42°F in rain in Flight No. 2.

(b) Droplet samples were obtained on every flight except the first and showed considerable variation both horizontally and vertically throughout the clouds. Tables and diagrams of the distributions are given in connection with the descriptions of the individual flights. Usually droplets about 100 μ and 200 μ diameter can be clearly seen on the aircraft's windscreen and rain is then reported. Hence in the case of the large clouds where ice crystals were present and the Bergeron process possible drop sizes of 100 μ diameter or more were expected and in fact were seen on the windscreen and were also measured by the sampling process. But in Fights 6, 7 and 8 which were through a cumulus cloud extending above the freezing level but not containing ice crystals droplets of this size were also measured. In addition large droplets were found during Flight 4 in a cumulus cloud which did not reach the freezing level and in Flight 5 which was made through small cumulus cloud intermixed with stratocumulus sheet with tops well below the freezing level. Small droplets were also of course always measured so that the droplet spectrum in all cases was very wide. This indicates that the coalescence process was generally very active in all the cumulus and stratocumulus clouds examined. In all cases there were reports of rain or drizzle within and below the cloud although it may not always have reached the ground. Only in Flights 1, 2 and 3 would it have been possible for the Bergeron process to have been the primary cause of the rain drops. The air was

/predominantly

predominantly maritime in origin throughout the period of these experiments so that sea salt nuclei would almost certainly have been available for the necessary condensation process to form large droplets which would initiate the coalescence process. The large horizontal variations of droplet spectra are ascribed to different stages of the coalescence process being reached in different cells in addition to the effect of sampling at different points in the same cell.

(iv) Vertical motions and turbulence

(a) Vertical motions averaged over distances of about half a mile were usually less than 5 feet per second even in the larger clouds. Occasionally, however, values of up to 20 feet per second were recorded.

(b) Turbulence was very variable. In most cases values of 0.3g (a value which makes writing or movement in the aircraft difficult and which is very uncomfortable if maintained for a period of time) were the maxima encountered in and below the clouds. Frequently the maximum value in the traverses was only 0.1g. Bumpiness was encountered in new hard towers at the tops of the clouds while the traverses through the crystal portions and anvils of the cumulonimbus clouds were generally quite smooth. The roughest conditions occurred in the precipitation areas about half way up the clouds both above and below the freezing level. Thus Flight No. 3 gave bumps of 0.5g in rain at 9,000 feet temperature 36°F in a cloud with base at 3,000 feet, tops 15,000 feet. Bumps of 0.7g were observed in Flight 8 at 13,000 feet temperature 23°F and 15,000 feet temperature 12°F in a cloud with base at 3,000 feet and tops 17,000 feet. It is interesting to note that in this latter flight only large water droplets were present and no change to ice crystals had yet taken place when the measurements were made. The largest bumps usually coincided with the probable cell boundaries or start of an up or downdraught. There was a tendency for the bumps to become more frequent towards the base of the cloud.

(v) Water content and icing

(a) Both water content and rate of icing tended to rise towards the centre of the cells. There was also a tendency for water content to rise with altitude except near the tops where it fell away rapidly. Water content always varied very rapidly with distance across a cloud, but it tended to be more uniform at the lower levels. Even its peak value very rarely approached that which would be calculated from adiabatic lifting considerations so that it appears certain that at some stage mixing or entrainment must be a very important factor in the development of the cloud.

(b) Icing was reported at temperatures between -9°F and 32°F. The former observation was taken in a hard cumulus top at 22,000 feet adjacent to a cell which had already developed an anvil in which there was no icing. In the same hard top at 19,000 feet and +2°F a maximum value of 2 gm/cu.metre was recorded. In another case 1.2 gm/cu.metre was found at 13,000 feet temperature 22°F during a traverse in which crystals, snow, hail and droplets were all observed.

(vi) The field below the cloud base

The work on this aspect was disappointing during these particular flights due to instrumental failures. More successful experiments have since been made and will be reported elsewhere. Some features however were apparent and these are listed below:-

(a) The vertical motions were usually smaller than in cloud and became more coherent from the ground upwards. The cell size was smaller than in cloud being usually half a mile to a mile in horizontal extent.

/(b)

(b) Temperature tended to rise in rising air and fall in descending air, particularly close to cloud. The temperature excess was about 0.3°F and the deficiency somewhat smaller.

(c) Below cloud well marked downdraughts were usually associated with rain areas.

Discussion

The object of this type of work is to gain a knowledge of the various cloud parameters and how and why they develop during the life of the cloud.

A certain amount of progress has been made in the instrumental field towards that end as water content, icing rate, vertical motions and turbulence can now be measured whilst droplets and crystals can readily be sampled in flight. There are however several large gaps in the instrumental equipment for this work such as accurate temperature measuring devices in cloud, instruments for measuring rain drop size and water content, instruments for measuring water content in ice crystal cloud etc. and work is continuing to develop these and also to improve existing instruments.

It appears that the present technique of measurement is inadequate as the life cycle of a given cumulus cell is usually about half an hour and the method of five or six successive traverses at different levels by the same aircraft takes about an hour. This means that the observations at one level are taken at different stages of a given cell's development from those at other levels. A fuller investigation of a cloud would include simultaneous measurements at several levels at about 5 minute intervals over a period of an hour or so. This of course would involve the use of several aircraft. At present this is not possible but a new series of flights has now been started in which these successive measurements at a given level are made with one aircraft. This will give information on variations with time at given levels and supplement the present series.

As the eight flights described in this report are part of the larger series it is premature to draw any firm conclusions from them. Several points however are of interest and are listed below:-

1. The large effect of small changes in environment temperature on the cloud development.

2. The necessity for entrainment or mixing to explain the water content of clouds but the likelihood that it is only important at their lower levels.

3. The presence of large droplets and wide droplet spectra in clouds where the Bergeron process could not have been in operation and the consequent importance of coalescence as a factor in the development of rain.

4. The low frequency of occurrence of dendritic crystals compared with prismatic and columnar types.

5. The data on structure and size of the clouds, icing, water contents, vertical currents and turbulence is consistent with that obtained by other investigators.

Acknowledgments

Acknowledgments are due to F.O. Bavin, R.A.F., who flew the Hastings aircraft used during these flights. Though inexperienced on the type he flew with accuracy under what were often difficult circumstances.

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/Flight 1.

Flight 1. 5/8/52.

1. Execution of the Flight. An ascent was made to 22,000 ft. during which temperature and frost point was measured every 1,000 ft. from 1,000 ft. ICAN. Various cumulonimbus tops extended to an estimated height of 30,000 ft. or more and penetrated a sheet of cirrostratus, particularly in the east.

It was decided to investigate a maturing cumulonimbus whose top was about 25,000 ft. and three minute traverses were made through its centre at 22,000, 19,000, 16,000, 13,000 and 10,000 ft. It was found that dissipation had occurred at the base which by this time - about 30 minutes after the start of the experiment - had risen to about 9,000 ft.

The aircraft then returned to base.

2. The sounding and its relation to observed cloud features.

(a) Results of the aircraft ascent and the winds from the afternoon Larkhill radio sonde ascent are plotted on Fig. 1. Estimated surface temperatures and humidities for the Cranfield area at the time are also given. This ascent lay roughly along the 60°F saturated adiabatic line and was quite moist.

(b) Considering Fig. 1 it appears that:-

(i) The lowest cloud base was 960 mb. which by the parcel method would be produced by a surface temperature of 70°F and dewpoint 62°F. The actual surface temperatures over the area were 67°F and dewpoints 64°F at the time.

(ii) With a condensation level of 960 mb. and the temperature ascent having a lapse rate rather more than the saturated adiabatic lapse rate, cumulonimbus clouds to very great heights might be expected. A photograph of the cloud actually investigated is given in Fig. 2b.

(iii) These cumulonimbus clouds were in fact encountered and as there are considerable dry layers around 750 mb. and above 600 mb. there could not have been any considerable entrainment at these levels.

(iv) The beginning of the lower dry layer coincided with the top of a stratocumulus layer. Thin stratocumulus cloud layers mixed in with the cumulus clouds might have been expected at about 800 mb. and 600 mb. from considerations of stability and humidity. In fact the only well marked stratocumulus layer occurred at about 800 mb. where well marked lenticular shapes were observed (Fig.2a).

The stabilising of the lapse rate from 910 mb. to 875 mb. coincides with the tops of small cumulus clouds.

3. Results of the traverses. The main cloud features are summarised in Table 1 and short notes on these features follow:-

(a) Cloud structure. The cloud under investigation had lateral dimension 10 miles and contained two cells at most levels all of lateral dimensions 2 - 3 miles. Of these the older cell lay to the south, i.e. upwind, and was almost entirely composed of ice crystals; from it was generated the anvil. The most active, northern, cell contained supercooled water droplets and caused aircraft icing.

(b) Composition. Ice crystals were sampled at all heights and a detailed description of the results is given in Table 2. The variation in type, after allowance for the presence of vertical motions, roughly follows that suggested by Nakaya[4]. The type was predominantly single plates with a few columns and there were indications of an increase of the size of single plates and aggregates towards the cloud base.

/Measurements

Measurements of droplet size were unsuccessful, probably due to the destruction of the MgO slide coating by ice crystals in the upper-regions of the cloud; in the lower regions no attempt was made due to the risk of lightning strikes. This risk was considerable as precipitation static was strongly evident on the aircraft V.H.F. system. No direct observations were made of precipitation but precipitation static was encountered at levels below 16,000 ft. in both the old cells.

(c) Vertical motions and turbulence. No violent up or downdraughts were measured, the normal value, averaged over half mile intervals, being 5-8 ft./sec. Turbulence was moderate and never exceeded an estimated 0.3g. It was usually experienced at the boundary between vertical currents of opposing sense and was most noticeable in the lower regions of the cloud.

(d) Water content and icing. Icing was encountered only in the northern cell and at temperatures between -11 and +12°F. Water content varied considerably both horizontally and vertically throughout the cloud. Values of 0.7 g/m^3 were measured at the base and a peak value of 2.0 g/m^3 was recorded by the icing meter at 22,000 ft.

(e) Field below cloud base. No observations were made below cloud base.

Table 1.

Main cloud features of decaying cumulonimbus investigated in Flight 1.

Cloud Traverses

Height feet	Mean Temp. °F.	Turbulence Max g	Turbulence Mean g	Icing Max g/cu.m.	Icing Mean g/cu.m.	Water Content Max g/cu.m.	Water Content Mean g/cu.m.	Extent miles	No. of cells	Remarks - composition
22,000	-9	.3	.1	.85	.1	-	-	7	2	Cell 1 Droplets 2 Crystals
19,000	+2	.1	.1	2.1	.6	-	-	9	2	Cell 1 Droplets 2 Crystals
16,000	+12	.2	.2	un-serviceable		.6	.4	10	1	Mixed Droplets and Crystals Precipitation Static.
13,000	+23	.3	.2	un serviceable		.2	.1	4	2	Cell 1 Droplets 2 Crystals Precipitation Static
10,000	+32	.3	.2	-	-	.7	.3	5	1	Mixed Droplets and Crystals.

/Table 2.

Table 2.

Analysis of cloud elements - Flight 1

Height ft.	Temp. °F.	Single Crystals: Plates Type	Plates Size	Plates Remarks	Columns Type	Columns Size	Columns Remarks	Aggregates Type	Aggregates Size	Aggregates Remarks
22,000	-11	Hexagonal and tetragonal	50-210μ	1:100 hollow	Hexagonal oval	420 x 70μ		Branched chains	350-700μ	
19,000	+1	Hexagonal and tetragonal, half each	50-270μ	Hexagons rather bigger				Chains of drops and crystals 1:100 have stellar tendencies	350μ	1:20 of smaller tetragons had 80μ droplets on their points. Drops often branch without merging.
16,000	+12	Hexagonal and tetragonal in ratio 20:1.	20-350μ	Tetragons have preferred direction of growth.				Chains, occasionally closed.	1100μ	1 in 100 tetragons had 80μ droplet on point. 1 in 150 dendritic.
13,000	+22	Hexagonal and tetragonal ratio 1:5.	20-170μ					Irregular, a few un-branched chains.	900μ mainly but some 500-1000μ	
10,000	+31	Hexagonal and tetragonal	35-100μ	Some had stellar hollows in centre.	Capped columns	350 x 100μ, caps 140μ	Occasionally 200 x 120, caps 170	Mainly massy aggregates.	700-1000μ	Some dendrites, some individual hexagons of 350μ with preferred direction of growth.

/Flight 2.

Flight 2. 6/8/52.

1. Execution of the Flight. During the morning a Mosquito aircraft made a temperature sounding above Cranfield, and also observed the heights of the bases and tops of the various cloud layers.

In the early afternoon the Hastings aircraft made a further sounding over Cranfield to 18,000 ft. ICAN. Thereafter a mature cumulus congestus was selected for investigation and traverses made through it at 18,000 and 15,000 ft. and the cloud then abandoned because of rapidly advancing decay which appeared to be occurring from the base upwards. A new cloud was selected which was growing in the Kettering area and traverses made above at 14,000 ft. and then through it at 13,000 ft. and subsequently at 2,000 ft. vertical intervals to 5,000 ft. Below cloud base runs were made with the ultra-rapid thermometer and the non-directional hot wire anemometer at 3,000, 2,000 and 1,000 ft. respectively.

2. The ascents and their relation to cloud features. The aircraft ascents and the winds from the afternoon Larkhill radio sonde ascent together with the estimated surface temperature and dewpoints in the Midlands are given in Fig. 3 and Fig. 3a.

Considering Fig. 3 it appears that:-

(a) The lowest cloud base was 915 mb. in the afternoon which is consistent with an estimation based on the parcel method and a surface temperature of about 74°F and dewpoint of 62°F. The actual values in the area that afternoon were temperatures 68°F to 70°F and dewpoints about 63°F.

During the morning the Mosquito observations showed small cumulus from about 950 to about 920 mb., a thin stratus layer at 880 to 850 mb., a stratocumulus layer from about 810-795 mb., some altostratus at about 610 mb., with some cumulus tops growing through it, and in the distance, both to east and west, large cumulus and cumulonimbus clouds were seen. In addition there was 7/8 of cirrus or cirrostratus cloud above 450 mb. so there can have been no lack of ice crystals in the atmosphere at high levels.

(b) Cumulus forming at the condensation level of 915 mb. in the afternoon could readily ascend to heights above the maximum of the aircraft sounding and this was confirmed by observations of many large cumulus and cumulonimbus clouds as well as being expected from the Mosquito observations.

Some photographs of these clouds are shown in Figs. 4a, b, c, and d.

(c) The humidity sounding shows a comparatively dry layer at about 700 mb. If there was any entrainment at this level it apparently made very little difference to the development of the cumulonimbus clouds.

(d) One stratocumulus layer was observed at about 760 mb. just below the comparatively dry layer. This layer can be seen clearly in Fig. 4c. The reason for its existence is not obvious from the tephigram although humidity was generally high at this level, and the wind is generally changing there from a southeasterly to a southwesterly regime.

3. Results of the traverses made. The main cloud features are summarised in Table 3 and short notes on these features follow:-

(a) Cloud structure. The cloud investigated appeared to consist of three cells, 2 miles, 4 miles and 2 miles wide respectively. The southern (upwind) cell was in an advanced stage of growth and contained a downdraught and rain. Dissipation appeared to be taking place from the base upwards but this may have been a result of the "direction" of investigation - from the top

/downwards.

downwards. The central cell was mature and contained both up and downdraughts, with rain in the updraught, whilst the northern cell was small and probably in an early stage of growth. There are indications that the 7,000 ft. traverse was rather off course and did not pass through this cell.

(b) Composition. Ice crystals were found only at 11,000 ft., apparently in the central cell, and they were mainly hexagonal columns and tetragonal plates. This was a region of mixed crystals and droplets. As cloud top temperature was 23°F presumably some natural seeding was taking place from other ice clouds.

Droplets were sampled at all heights but there were no systematic trends in sizes, presumably due to the random manner in which sampling was done relative to the cells. Some very large droplets of diameters up to 500 μ were observed in the 7,000 - 9,000 ft. region. Details of the cloud elements are given in Table 4.

(c) Vertical currents and turbulence. Up and downdraughts averaged over about half a mile were usually less than 10 ft./sec. but an updraught decreasing in strength upwards from 10-15 ft./sec. was observed in the rain area of the central cell. Downdraughts of about 5 ft./sec. were encountered in the run over the cloud particularly on the north side. Turbulence was quite moderate at all levels being less than an estimated 0.3g; in all but the lowest levels it could be associated with the shear zone between vertical motions of opposing sense.

(d) Icing and water content. No icing was recorded or reported though it seems likely that there may have been slight icing in the top of the mature cell, where the rate of icing may have been below the capacity of the rotating disc meter.

Peak water content was 0.8 g/m^3 and at 9,000 ft. Water contents in the lower regions were more constant than in the higher.

(e) Field below cloud.

3,000 ft. At this level a rain area 2 miles wide apparently associated with a single cell was encountered. Vertical motions were generally less than 5 ft./sec. Downdraughts were strongest in the rain area where they had apparent temperature deficiencies up to 2°F but the most common excess or deficiency in the draughts was only about 0.1°F. Temperatures tended to be higher under firm cloud bases and this was also the most common updraught region. Gusts were usually very small except for one sharp edged gust at the edge of a downdraught associated with the rain area.

2,000 ft. This was a region of small and apparently random vertical motions less than 5 ft./sec. with temperature variations usually less than 0.2°F. There was however one variation of 0.5°F associated with an updraught. Downdraughts and lower temperatures tended to coincide with breaks in the cloud above, and were again most evident in the rain area. A sharp edged gust was recorded at the edge of a 5 ft./sec. downdraught at the edge of an overcast region.

1,000 ft. Vertical motions were more pronounced at this level and reached about 10 ft./sec. Temperature pulses of ±0.2°F were frequent and usually had a horizontal extent of about 300 yards. On one occasion there was a downdraught of 5 ft./sec. under cloud with an updraught of 10 ft./sec. under the surrounding blue sky and this updraught appeared to have a temperature excess of 0.4°F. Gusts of 5 to 10 ft./sec. were general and were most frequently found at the edges of up or downdraughts.

/Table 3.

Table 3.

Main cloud features of maturing cumulus congestus investigated in Flight 2.

Cloud Traverses

Height feet	Mean Temp. °F.	Turbulence Max g	Turbulence Mean g	Icing Max g/cu.m.	Icing Mean g/cu.m.	Water Content Max g/cu.m.	Water Content Mean g/cu.m.	Extent miles	No. of cells	Remarks - composition
13,000	23	.2	.2	-	-	.2	.2	1	1	Droplets.
11,000	30	.2	0	-	-	.5	.1	2	1	Mixed droplets crystals and rain.
9,000	36	.3	.2	-	-	.8	.6	6	3	Droplets and rain.
7,000	42	.3	.1	-	-	.6	.2	4	2	Droplets and rain. Precipitation static.
5,000	49	.2	.2	-	-	.7	.3	5	2	Droplets and rain.

Table 4.

PROJECT CU. - FLIGHT 2

Maturing cumulus congestus

Height feet	Temp. °F.	Water Droplets	Ice Crystals
13,000	+24	14-40 μ, mainly 20 μ. Density about 300/cm^3.	Nil.
11,000	+29	7-30 μ, some 55-110 μ. Density about 300/cm^3.	Hexagonal columns 50 x 30 μ, and tetragonal plates.
9,000	+36	7-30 μ and 55-110 μ. Density about 300/cm^3.	Nil
7,000	+42	7-55 μ, but some 80-500 μ, of which most are < 350 μ. Density about 200/cm^3.	Nil.
5,000	+49	Mainly 7-10 μ. Density about 300/cm^3.	

/Flight 3.

Flight 3. 7/8/52.

1. Execution of the Flight. During the afternoon a sounding to 22,500 ft. ICAN was made over Cranfield in the Hastings aircraft and a developing cumulus lying to the north of Cranfield subsequently chosen for investigation. Traverses were made through it at 15,000 ft. and thereafter at 2,000 ft. vertical intervals to 3,000 ft. In addition crystal samples were obtained in an altostratus layer from 19,000 to 23,000 ft. at 1,000 ft. intervals.

2. The soundings and their relation to observed cloud features. The results of the soundings have been plotted on Fig. 5. Considering this diagram:-

(a) From parcel method calculations the lowest condensation level would be at about 930 mb. with a surface temperature of about 70°F and a dewpoint of 60°F. Observed surface values in the area were about 66°F and 59°F respectively.

The main cumulus cloud base appeared to be at about 930 mb. but fractocumulus was reported at much lower levels. At these very low levels it was very moist and condensation was observed over the aircraft wings.

(b) Upper air conditions on this ascent were rather more stable than on Flights 1 and 2. There are several small decreases in the lapse rate e.g. at 880 mb. (which agreed with the tops of the fractocumulus layer), 780 mb., 640 mb. and 510 mb. which would tend to stop vertical motion and also an altostratus layer above which must have reduced surface heating. This ascent was, however, made rather near to a front which was giving rain over England south of the Thames and it appears probable that the large cumulus clouds were due at least in part to general convergence in the area.

(c) There was a very dry layer at about 680 mb. while cumulus tops were extending to at least 600 mb. so it appears that, in this case also, entrainment at these levels is not considerable. The very dry layer started at the top of a thin altostratus layer.

(d) The nearness of the frontal cloud and the presence of the high altostratus layer must certainly have provided a good source of ice crystals for natural seeding in the area.

(e) Conditions were poor for aerial photography during this flight and the photographs obtained were not worth reproducing.

3. Results of the traverses. The main cloud features are summarised in Table 5 and short notes on these features follow:-

(a) Cloud structure. The cloud proved to be a complex of two cells, of which the most easterly -cell 1- was dissipating and the other -cell 2- reaching maturity. Cell 1 was surmounted by pileus when first investigated and in its upper portions regions of rain, snow and hail could be distinguished. Rain was confined to the most easterly portion and did not appear to reach the ground. The cell contained an updraught in the upper portion but a downdraught was observed later in the lower levels. Cell 2, which was separated from Cell 1 by a gap about half a mile wide, set in the shear zone between an updraught and a downdraught, was in the rain stage save for a small snow region in the uppermost portion of the cloud. The general rain intensity appeared to increase fairly regularly to a maximum near the centre of the cloud at all levels. The maximum lay in a fairly strong updraught and from this region rain appeared to reach the ground.

(b) Composition. Details of the droplet and ice crystal sampling in both the altostratus and the cumulus cloud are given in Tables 6 and 7.

/The

The ice crystals, which were sampled in Cell 1 of the cumulus cloud in its upper 2,000 ft., i.e. at temperatures less than about +22°F, were predominantly hexagonal plates of diagonal dimension 20-170μ in aggregates of about 700μ diameter. Some dendritic structures were present, however, in the region of rain development in the extreme top of the cloud. Sometimes the aggregates contained droplets of diameter 10-60μ attached to the ice crystals.

Water droplets were of approximately equal density - 700/cm^3 - at all heights and basically of fairly constant width of distribution. The majority of droplets sampled appeared to have diameters of less than 10μ although 10-20μ was also common. Large droplets of 100μ diameter or larger were present at all levels. There was a maximum width of the superimposed rain spectrum at 9,000 ft.

The altostratus was composed of plate and columnar crystals. The latter were about 200μ long and were more common at the higher levels. The former increased in size from 170μ to 350μ diagonal length between 23,000 and 20,000 ft. Some 14μ diameter droplets were observed in the altostratus at 20,000 ft. where the temperature was -3°F.

(c) Vertical motions and turbulence. Vertical motions averaged over half a mile, did not normally exceed 10 ft./sec.

Turbulence was rather higher than usual, reaching a maximum estimated value of 0.5 g at 9,000 ft. and becoming more probable at the lower levels.

(d) Water content and icing. Icing was encountered only during the 13,000 ft. traverse and at about +23°F. A peak value of 1.2 g/m^3 was recorded.

Water content was quite variable at all levels, a peak value of 0.95 g/m^3 being recorded at 9,000 ft.

Visibility at the 9,000 and 7,000 ft. levels was often 5 yd. or less.

The hot cylinder water content meter although designed primarily to measure water content in cloud gave readings between 0.1 and 0.4 gm/m^3, in the rain area underneath the cloud. These must be regarded as minimum values as the collecting head of this instrument is too small to work efficiently as rain collector.

/Table 5.

Table 5.

Main features of developing cumulus investigated in Flight 3.

Cloud Traverses

Height feet	Mean Temp. °F.	Turbulence Max g	Turbulence Mean g	Icing Max g/cu.m.	Icing Mean g/cu.m.	Water Content Max g/cu.m.	Water Content Mean g/cu.m.	Extent miles	No. of cells	Remarks - composition
15,000	17	.3	.2	Not recorded		.6	.5	1	1	Mixed (crystals (droplets light rain
13,000	22	.3	.2	1.2	.8	.6	.4	3	1	Mixed (crystals (snow (hail (droplets
11,000	28	.3	.2	Not recorded		.7	.3	6	2	Mixed (droplets (rain (snow
9,000	36	.5	.3	Nil		1.0	.6	9	2	droplets rain
7,000	40	.3	.2	Nil		.7	.5	6	2	droplets rain
5,000	47	.3	.2	Nil		.7	.5	9	2	droplets rain
3,000	53	.2	.2	Nil		.4	.2	4	1	droplets rain

Table 6

PROJECT CU - FLIGHT 3

Composition of cumulus cloud

Height feet	Temp. °F.	Water Droplets	Ice Crystals
15,000	21	Mainly 5-10μ, occasionally 140-240 μ.	Mainly a complicated dendritic structure in aggregates up to 170 μ across. Some droplets, included in structure, of 10-40μ diameter.
13,000	23	Mainly 14-40 μ, occasionally 5 and 80μ. Density variable between 150 and 700/cm^3.	Tetragonal and hexagonal plates of 20-170μ in aggregates up to 700 μ. Some single crystals with droplets attached. Separate droplets of 10-55μ.
11,000	29	Mainly 7-10 μ but occasionally 7-20μ. Fair number of 200-240 μ and apparently some snow.	None

/9,000

Table 6 continued.

Height feet	Temp. °F.	Water Droplets	Ice Crystals
9,000	About 36	Mainly 5-10μ, occasionally 60-80μ and a few 350μ and one 1100μ.	None
7,000	About 40	Mainly 10-20μ but some areas of 20-30μ. Occasionally 60-110μ. Probably 700/cm^3.	None
5,000	48	Mainly 5-10μ but some areas of 20-40μ diameter. A few 120-380μ. Density variable between 500 and 700/cm^3.	None
3,000	54	Mainly 14-40μ and a few 100-350μ diameter. Density less than 100/cm^3.	None

Table 7

PROJECT CU - FLIGHT 3.

Composition of altostratus cloud

Height feet	Temp. °F.	Water Droplets	Ice Crystals
23,000	-15	Nil	Some tetragonal and a few hexagonal plates, but mainly hexagonal columns or a tending to columnar development. Plates mostly 170μ diameter but some 20-100μ. Columns 210μ long x 70μ or less broad. Few double or treble crystals, no aggregates.
22,000	-10	Nil	Mainly hexagonal plates with a few tetragonal plates and hexagonal columns. Plates mainly 20-60μ with a few 90μ diameter stellar tendencies, some tetragons aggregated in dendritic forms.
21,000	-6	Nil	Tetragonal plates and short columns. Plates 20-240μ diameter, columns 100-170 x 70-100μ, but mainly 200 x 80μ. Often three or four columns joined by what appears to be a frozen droplet.
20,000	-2	Occasionally 14μ diameter.	Hexagonal and tetragonal plates, hexagonal predominating. A few short columns 100 x 70μ. Plates 20-350μ diameter but mainly about 170μ. Many aggregates up to 1400μ across and chains of 500μ long. Plates show internal ribbing.

/Flight 4.

Flight 4. 8/8/52.

1. Execution of the Flight. The investigation took place between 1100 and 1430Z. After a sounding up to 10,000 ft. ICAN had been made over Cranfield a developing cumulus about 50 miles NNE of Dunstable was selected for investigation and traverses made at 8,000 ft. (above cloud tops) 6,500, 5,500, 5,000, 4,500 and 4,000 ft. (in cloud).

2. The soundings and their relation to observed cloud features. From the ascent which is shown on Fig. 6 it appears that:-

(a) From the parcel method, a surface temperature of 67°F and a dewpoint of 54°F would lead to a cloud base of about 900 mb. which agrees quite well with the observations made.

(b) Cloud tops however might have been expected to extend to 760 mb. In fact the tops were observed to be at about 810 mb. which coincides with a small layer of decreased lapse rate.

(c) The increase of temperature of the ambient air at 810 mb. required to stop vertical motion there is less than 1°F. This observed height of cloud tops might be accounted for by quite a small amount of entrainment or mixing around and just below this level where it is comparatively dry.

(d) Photographs of the clouds investigated are given in Figs. 7a and 7b.

3. Results of the traverses. The main cloud features are summarised in Table 8 and short notes are given on them below:-

(a) Cloud structure. A complex of clouds was investigated which consisted of two main clouds each 1-2 miles wide and 3,000 ft. deep and having a small cloud of the same width and 1,000 ft. deep to the south of it. In each case it appeared that the subsidiary clouds, situated in or closely associated with descending air, were the products of decay of old cells.

The most northerly (downwind) cloud was remarkable in that it appeared to be set in an ascending environment at all heights, within downdraughts occurring within the cloud itself. Rain was observed in the absence of ice crystals (the lowest temperature recorded in the cloud was +34.2°F). Presumably ice crystals could be present in the atmosphere above the freezing level but as this cloud was everywhere below it any rain within the cloud must have been due to another cause - probably coalescence. Rain was also observed in the southerly cloud where it appeared that the coalescence had advanced further.

(b) Composition. Droplets were sampled at all heights, and the maximum droplet diameter at a given level increased from 200 μ near the base of the most northerly cloud to 400μ (a small raindrop) near tops. In this cloud the droplet spectrum appeared to decrease in width with height as one would expect in the early stages of a simple coalescence process, though the model may be complicated, in fact, by the advance in time as the measurements were made. In the southernmost major cloud rain was also found, the diameter decreasing from 700 μ near base to 140μ near tops. The spectrum of droplet sizes was relatively constant, sizes ranging usually from 7 μ to 55μ. Details of the droplet sampling and the droplet distributions are given in Table 9; Table 10 and Fig. 8 give detailed distributions for the samples taken at 4,500 ft., 5,000 ft. and in rain close to cloud base.

/Coalescence

Coalescence was almost certainly the rain making process again in this latter cloud but the model is probably not so simple as in the previous case. Whereas previously one could envisage a process in which the larger droplets were swept up by the large drops found at the base, thus reducing the basic droplet spectrum width with accompanying increase in rain drop size and spectrum width, in this case it is reasonable to suppose that this process has already taken place and that sedimentation has reversed the trend in maximum drop diameter with height. The constancy of droplet spectrum width is a disturbing feature but this may well be ascribed to the ascent of fresh bubbles into an already mature cloud.

The most noteworthy feature of the whole investigation was the unusual width of the droplet spectrum and this must be the feature most responsible for the coalescence rain production. The air mass concerned was of maritime origin and it may be that the larger droplets were formed on giant salt nuclei as proposed by Ludlam [5]. The great variability of the results of successive samplings within short distances is also notable.

(c) Vertical motions and turbulence. Vertical motions were usually small in the northern cell and never exceeded 15 ft./sec. when averaged over half a mile. The greatest velocities were observed at the lowest levels, i.e. late in time. In this cell rain was observed in descending air.

In the southern cloud velocities were generally less than 5 ft./sec. and were normally greater in the more southern regions. Here rain was found in ascending air and downdraughts were observed in its environment.

Traverses made below cloud indicated vertical motions of 1-2 ft./sec. but the general motion lacked coherence.

Turbulence was infrequent and small in both clouds and usually limited to the shear zones between vertical motions of opposing sense.

(d) Water contents were materially higher in the southern cloud than in the northern, values being generally about 0.5 g/m^3 in the one case and about 0.3 g/m^3 in the other.

Table 8.

Main cloud features of cumulus clouds investigated in Flight 4.

Cloud Traverses

Height feet	Mean Temp. °F.	Turbulence Max g	Turbulence Mean g	Icing Max g/cu.m.	Icing Mean g/cu.m.	Water Content Max g/cu.m.	Water Content Mean g/cu.m.	Extent miles	No. of cells	Remarks - composition
8,000	35	0	0	0	0	0	0	0	0	Over top of cloud in clear air.
6,500	40	.2	.1	Nil		.6	.3	2	2	Droplets Small rain drops.
5,500	44	0	0	Nil		.7	.3	2.5	2	Droplets Small rain drops
4,500	46	.2	.1	Nil		.4	.2	5	5 (2 small)	Droplets Rain drops.

/Later

Table 8 continued.

Cloud Traverses

Height feet	Mean Temp. °F.	Turbulence Max g	Turbulence Mean g	Icing Max g/cu.m.	Icing Mean g/cu.m.	Water Content Max g/cu.m.	Water Content Mean g/cu.m.	Extent miles	No. of cells	Remarks - composition
Later runs										
4,000	48	.2	0	Nil		-	-	4	3	Droplets
5,000	45	0	0	Nil		-	-	4	3	Droplets

Table 9

PROJECT CU - FLIGHT 4.

Composition of a developing cumulus cloud

Height feet	Temp. °F.	Water Droplets	Ice Crystals
6,500	42	Occasionally 100-400 μ but mainly 14-20 μ diameter. Density 3-400/cm^3.	Nil
5,500	44	Mainly 7-55 μ diameter, occasionally 80-230 μ. Density >> 500/cm^3, occasionally diminishing to 3-400/cm^3.	Nil
4,500	47	7-40 μ diameter, with some rain drops of up to 700 μ. Density 300/cm^3.	Nil
4,000	48	7-40 μ diameter, but mainly 15-20 μ. A background of very small droplets $\leq$ 4 μ. Density about 100/cm^3.	Nil
5,000	46	7-20 μ but mainly 10-15 μ diameter. Density 500/cm^3.	Nil

/Table 10

Table 10

Flight 4. 8/8/52.

Droplet distribution by volume

Droplet diameter "d"	Percentage of total by volume contained in droplets of diameter less than "d"					Height feet
	Sample 1	2	3	4	5	
μ						
11	5.6	0.7			1.1	4,500
17	5.6	0.7			1.1	
25	95.8	24.6			70.6	
35	100.0	34.5			93.3	
50		53.9			100.0	
70		92.8				
90		100.0				
Other sizes		1,700μ				
11	0.8	3.7	33.8	24.2		5,000
17	0.8	3.7	33.8	24.2		
25	66.5	82.9	100.0	100.0		
35	91.2	88.0			2.8	
50	95.9	100.0			6.3	
70	100.0				14.2	
90					25.8	
110					32.1	
130					42.9	
150					53.2	
180					64.2	
220					100.0	
11		0.1	0.1	0.4		Rain below base
17		0.1	0.1	0.4		
25	1.0	0.7	3.3	10.1	1.1	
35	2.3	7.9	6.3	18.3	5.4	
50	4.0	14.3	8.8	28.3	9.6	
70	4.0	16.3	30.0	46.3	18.5	
90	20.3	21.3	82.2	71.6	23.4	
110	22.0	38.3	91.5	82.4	33.4	
130	31.5	38.3	100.0	100.0	50.6	
150	46.1	38.3			58.5	
180	62.7	48.3			64.5	
220	62.7	67.5			70.3	
260	62.7	100.0			100.0	
300	100.0					

Flight 5. 12/8/52.

1. Execution of the Flight. The cloud on this occasion was mainly of a stratocumulus rather than a cumulus type, although it did contain some developing cumulus. Bases of the layer were generally 2,500 ft. and tops generally 3,700 ft.

Traverses were made below cloud at 700, 1,200, 1,700 and 2,200 ft. An ascent was made from 900 to 8,100 ft. during which observations were made every 200 ft.

Unfortunately records of the ultra-rapid thermometer which were made during these traverses were lost due to a camera fault; a certain amount of information is available from the readings of the flat plate thermometer, hygrometer, height and airspeed and visual observations.

/One

One traverse was made penetrating cloud tops and measurements of water content and droplet size obtained.

2. The sounding and its relation to observed features. The aircraft sounding - including winds from 1400Z Larkhill radio sonde - from 900 to 8,100 ft. is plotted on Fig. 9. Estimated surface temperatures and humidities for the Cranfield area at this time are also given.

Considering Fig. 9 it appears that:-

(a) Lowest cloud base was 925 mb. which is consistent with parcel method calculation based on a surface temperature of 69°F and surface dewpoint of 59°F. The actual values were:- Temperature 75°F, dewpoint 53°F.

(b) With this condensation level and ascent along a saturated adiabatic cloud top might be expected to be 860 mb. but was actually 885 mb.

(c) As there was a very dry layer also commencing at 885 mb. it appears likely that entrainment at this level was effective in limiting the cloud tops.

Drizzle was observed beneath cloud but was not actually observed to reach the surface.

3. The horizontal traverses above and below cloud. Summaries of the various traverses follow:-

(i) 2,200 ft. 33 miles under stratocumulus thinning after 12 miles, occasional breaks. A developing cumulus breaking through the sheet after 22 miles. Drizzle after 8 miles.

Updraughts and downdraughts were mainly random, about half a mile to a mile across and having strength 1-2 ft./sec. though exceptionally 3-5 ft./sec. at the beginning. There was no correlation with particular cloud features though a downdraught of 8 ft./sec. was associated with the drizzle.

Temperature rose unsteadily 1.8°F throughout the run; the gradient was normally about 0.2°F/mile but occasionally rose to 0.8 - 1.2°F/mile. There was a tendency for higher temperature to be associated with updraughts and lower to be associated with downdraughts in the case of the stronger currents.

Frost point varied between 54° and 57°F throughout the run, being lowest and most variable during the last half of the run when under broken cloud.

Turbulence was very slight rising to an estimated value of 0.1g only occasionally.

(ii) 1,700 ft. 22 miles under blue sky with only occasional wisps of cloud. Up and down currents were random and usually half a mile to a mile across and 1-2 ft./sec. in strength. A downdraught of 4 ft./sec. was observed near the middle of the run.

Temperature varied about 1.3°F throughout the run, usually at the rate of 0.2 - 0.4°F/mile though occasionally 1.6°F/mile. There was no strong correlation between direction of vertical motion and temperature differences though a strong downdraught was associated with a rapidly falling temperature.

Frost point was very steady at about +55°F.

Turbulence was estimated to be about 0.1g and was experienced over most of the run.

/(iii)

(iii) 1,200 ft. 17 miles half under blue sky, half under broken cloud. Up and down currents were random and usually half a mile to a mile wide and of speed 1-2 ft./sec. under blue sky. Under the broken cloud an upcurrent of speed > 2 ft./sec. and width about 2 miles was experienced. At the edge of the cloud sheet there was turbulent motion in which the vertical motion changed from > 11 ft./sec. upwards to > 8 ft./sec. downwards.

Temperature varied about 0.8°F between extreme values throughout, and was higher and more variable in the blue sky region. Temperature gradients were usually 0.2°F/mile but occasionally 1.0°F/mile. There was some correlation between direction of vertical motion and sense of temperature change beneath blue sky, but not beneath cloud.

Turbulence was estimated to be 0.1g and was rare, being experienced as broken cloud was approached.

(iv) 700 ft. 17 miles under wisps and broken cloud, cloud predominating in the first two thirds of the run.

Up and down currents were random with a slight tendency for up-draughts to be associated with wisps and downdraughts to be associated with breaks. Strength was normally 1-2 ft./sec. and width about half a mile.

Temperature varied about 1.3°F between extremes over the run, reaching a maximum value just before the cloud edge encountered after two thirds of the run. Gradients were generally 0.8 - 1.4°F/mile. There was no correlation between temperature and vertical motion.

Frost point was steady at 57°F.

Turbulence was estimated to be 0.1 - 0.2g.

(v) 4,000 ft. 25 miles entirely above cloud with three short penetrations into cloud.

Up and down currents were rather more coherent and less frequent than below cloud, and in general linked with the tops penetrated. Width was generally 1-2 miles and strength variable between 2 and 15 ft./sec., the highest value being observed in downdraught. Drizzle was observed in one top in an updraught.

Temperature, when corrected for changes of height, varied about 2°F between extremes during the run, tending to rise 0.6 to 0.9°F in cloud, although instrumental uncertainties make this last conclusion doubtful.

No turbulence was recorded.

4. Data obtained in cloud tops. Water contents were 0.5 g/m^3 in the updraught portions of cloud and 0.4 g/m^3 in the downdraught. A value of 0.25 g/m^3 was recorded in drizzle-bearing wisp of cloud. Cloud base temperature was about 57°F and cloud top temperature 51°.

Droplet diameters varied between 8 and 240 μ. The width of spectrum was quite variable ranging from 8 to 30 μ to 8 to 240 μ at the same height.

The water contents are less than a half of that anticipated from a saturated adiabatic ascent which tends to confirm the entrainment ideas suggested above.

The largest water drops are drizzle size and are often observed in clouds similar to those explored on this occasion. The large droplets found in this cloud must have been formed by a coalescence process which had been going on for some considerable time. This contention is supported by the fact that the cloud sheet had been in existence for about forty-eight hours.

/Flight

Flight 6. 13/8/52.

1. Execution of Flight. Horizontal runs were made at 500, 1,000, 2,000, 3,000 and 4,000 ft. partly beneath a sheet of stratocumulus, occasionally with mammato-form base, and partly under cumulus. This sheet of stratocumulus, which occupied the quadrant north west of Cranfield, had a base level at 7,700 ft. which was rather above that of the surrounding cumulus. Beneath it there was decaying cumulus which occasionally grew into and through the sheet. Some rain was observed below the stratocumulus. An ascent measuring temperature and frost points was then made to 12,000 ft.

On conclusion of the clear air work, runs were made in cloud tops at 10,000, and also at 9,000 and 8,000 ft. whilst on track for base.

2. The soundings and their relation to observed cloud features. The ascent is plotted on Fig. 10 and the following notes are given:-

(a) From parcel method considerations, a surface temperature of 74°F and a dewpoint of 51°F would have been necessary to produce a condensation level at 830 mb. Unfortunately we have no good observation of the height of the cumulus base. The stratocumulus base which was somewhat higher was at about 750 mb.

(b) With this condensation level cumulus tops might have been expected to extend to 740 mb. and occasionally 650 mb. There was only a small "stop" at the former but at the latter there was a well marked inversion and a considerable decrease in the frost point. Tops were actually at 680 to 690 mb., just below the inversion.

(c) Surface temperatures in the Cranfield area may not quite have attained the value of 74°F as the reported 1200 and 1500 hours temperatures are 70°F. This would be consistent with the fact that the cumulus clouds were rather sporadic and tending to decay during the afternoon and the stratocumulus layer may have been mainly the result of a small zone of wind shear between 800 and 750 mb.

(d) Photographs of the clouds are given in Figs. 11 a and b.

3. Results of the traverses below cloud. These will not be described in detail as they were very similar in execution to those made in Flight 5. Each run was about 8 miles in length. The main features are summarised below:-

(i) Rain was encountered both at 4,000 and 3,000 ft. It was associated with well marked downdraughts 1 to 2 miles across on each occasion.

(ii) Elsewhere up and downdraughts were small probably almost always less than 5 ft./sec. and usually randomly distributed. Their extent varied from ½ to 2 miles across. At 4,000 ft. and 3,000 ft. the downdraughts were mainly on the south side and the updraughts on the north side of the clouds while under clear skies there were usually small downdraughts. Downdraughts were noticed under the mammato base of the stratocumulus cloud.

(iii) Temperature variations were about 0.5°F in a half a mile and the excess in updraughts was about 0.3°F, the deficiency in downdraughts being generally smaller. At 2,000 ft. and below there was no apparent correlation between temperature variation and the direction of vertical motions.

(iv) Turbulence was generally less than 0.2g and became less probable with increase in height. At 3,000 ft. turbulence was confined to the edges of cloud and at 4,000 ft. no turbulence greater than 0.1g was observed.

/4.

4. Run above cloud at 11,000 ft. This was above cloud tops and mainly in a downdraught area where it was noted that temperature was about 1.5°F less than in corresponding updraught areas.

5. Runs in cloud. The main features are given in Table No. 11 and the following additional remarks are given:-

(a) Cloud structure. The clouds investigated were predominantly stratocumulus with only occasional cumulus. Most of the phenomena appeared to vary systematically over distances of 2-3 miles in the lower portion of the cloud and 1-1½ miles in the upper portion. Rain was encountered at all heights and was heaviest in the tops.

(b) Composition. Droplet samples were obtained at all heights and details are given in Table 12. In Table 13 and in Fig. 12 results of successive samplings at 200 yd. intervals are shown. Photographs are also shown in Figs. 13 a and b of the type of samples obtained. The droplet spectrum appeared to vary irregularly throughout the cloud while the drizzle or raindrop size increased towards the base. No crystals were found and there was no icing although cloud tops were slightly higher than the freezing level.

There was higher cloud in the area which might possibly have provided a source of ice nuclei but it appears more likely that coalescence was the principal factor in producing drops of rain size from this cloud. The droplet spectra tend to support this view, and it appears that whereas in some parts of the cloud the coalescence process was well advanced in others it was in an early stage.

(c) Vertical motions and turbulence. Up and downdraughts were ill defined both near the base and the tops of this cloud but in the central portions appeared occasionally to exceed 10 ft./sec.

Turbulence was generally between 0.1g and 0.2g and was frequent near the base of this cloud.

(d) Water content and icing. As cloud top temperatures were about 29°F kinetic heating effects would have been sufficient to prevent any icing.

Water content was very variable at all levels and reached peak values of 0.5 g/m³ both at the tops and in the base of the cloud. It appeared to be rather less in the middle. It was noticed that the highest water content measurements tended to coincide with the rain areas.

Table No. 11

Composition of stratocumulus cloud investigated in Flight 6.

Cloud Traverses

Height feet	Mean Temp. °F.	Turbulence Max g	Turbulence Mean g	Icing Max g/cu.m.	Icing Mean g/cu.m.	Water Content Max g/cu.m.	Water Content Mean g/cu.m.	Extent miles	No. of cells	Remarks - composition
10,000	29	.2	.1	Nil		.5	.2	8	Several (Cu. and St.Cu.)	Droplets and Rain.
9,000	30	.2	.1	Nil		.3	.1	8	Several (Cu. and St.Cu.)	Droplets Rain.
8,000	35	.2	.1	Nil		.5	.2	8	Several (Cu. and St.Cu.)	Droplets Rain

/Table

Table 12

PROJECT CU - FLIGHT 6

Composition of stratocumulus cloud

Height feet	Temp. °F.	Water Droplets	Ice Crystals
10,000	28	Mainly 10-20 μ diameter but some 30-40 μ and a few 100-350 μ. Density 200-300/cm^3.	None
9,000	30	Early samples: Mainly 10-55 μ diameter with greater concentration around 10 μ and 55 μ. A few 350 μ. Density 200-300/cm^3. Later samples: Mainly 7-20 μ with greatest concentration at 10 μ. Occasionally 60 μ. Density 300-400/cm^3.	None
8,000	35	Early samples: Mainly 10-40 μ but some 350-520 μ. Density 400/cm^3. Later samples: Mainly 14-40 μ with some 70-220 μ. Density 100/cm^3.	None

Table 13

Flight 6. 13/8/52.

Droplet distribution by volume

Droplet diameter "d"	Percentage of total by volume contained in droplets of diameter less than "d"					Height feet
	Sample 1	2	3	4	5	
μ						
11	0.3	0.1	0.1		0.1	8,000
17	0.3	0.1	0.1		0.1	
25	3.1	8.4	7.6	0.9	4.9	
35	17.7	13.1	20.0	3.2	21.9	
50	37.0	20.0	30.6	8.7	35.9	
70	83.7	48.6	48.7	30.4	71.0	
90	100.0	61.0	59.4	48.0	87.0	
110		79.1	59.4	58.3	87.0	
130		100.0	66.6	78.9	100.0	
150			66.6	78.9		
180			100.0	90.0		
220				100.0		

/Flight 7.

Flight 7. 14/8/52

1. Execution of the Flight. An ascent was made to 20,000 ft. ICAN in the Mosquito aircraft in the morning and further measurements were made with the Hastings aircraft in the afternoon.

After the Hastings sounding of temperature and humidity over Cranfield from 1,000 to 9,000 ft. it was decided, in the absence of any large cumulus, to concentrate on clear air runs below cloud base level; owing to the recording camera fault previously mentioned much of the information from the ultra-rapid thermometer was lost.

Horizontal runs were made at 9,000, 8,000, 6,500, 6,000, 5,500, 4,000, 2,000, 1,000 and 500 ft. ICAN. Cloud base in the afternoon was 5,300 ft. and tops 8,000 ft. and data on conditions within the cloud were obtained on the 8,000 and 6,500 ft. runs, the 6,000 ft. run being entirely in clear air.

2. The soundings and their relation to observed cloud features. The results of the 1100Z Mosquito ascent and the 1500Z Hastings ascent are plotted on Figs. 14 and 15. Considering these diagrams:-

(a) (i) From parcel method calculations the lowest condensation level at 1100Z would be about 840 mb. (actual value 850 mb.) with a surface temperature of about 68°F and dewpoint of 47°F. Observed surface values at this time were about 68°F and 53°F. The water content line above 950 mb. suggests that parcels originate mainly in the layer beneath 950 mb.

(ii) Similar calculations show that the lowest condensation level at 1500Z would be at about 815 mb. (actual value 840 mb.) with a surface dewpoint of about 45°F and temperature of 70°F. Observed surface values at this time were 69°F temperature and 55°F dewpoint.

(b) (i) There was an isothermal layer between 780 mb. and about 720 mb. at 1100Z which effectively limited penetration by parcels to about 760 mb. a value in good agreement with the observed tops at 745 mb.

(ii) The ascent made at 1500Z indicates a small inversion - of 3°F - between 750 and 720 mb. which would limit tops to about 740 mb. - the observed tops being at about 750 mb.

(c) (i) The 1100Z ascent indicates a marked drying of the air above 870 mb. which indicates that entrainment cannot have been a significant feature in development at this stage.

(ii) The 1500Z ascent is quite moist to 750 mb. above which there is pronounced drying. The change since the morning must presumably be ascribed to convective transport of water vapour upwards. Even so, surface dewpoints are surprisingly high compared to those measured at the lowest point in the aircraft ascent. Normally when there is considerable convection taking place only a very small hydro-lapse would be expected if there were much mixing with the environment. In this case it must be concluded that any air taking part in cloud formation must have originated below 950 mb. in the morning and below 980 mb. in the afternoon - both these pressures being relative to a corrected surface pressure of 1013 mb.

3. Runs below cloud. These runs, which were made at heights of 4,000, 2,000, 1,000 and 500 ft., showed features very similar to those described in connection with Flights 5 and 6.

(i) Vertical motions were small but occasionally speeds of about 5 ft./sec. were measured. These up and downdraughts were more organised below 2,000 ft. than above and were then between 1 and 2½ miles in extent. Higher up they were more randomly distributed and no size can be given. Small downdraughts again usually occurred beneath clear sky while both up and downdraughts were noted below cloud.

/(ii)

(ii) The temperature varied by about 0.5°F in half a mile but there seemed to be no correlation between the regions of higher or lower temperature and the direction of the vertical motions.

(iii) Turbulence at all levels was usually less than 0.1g but bumps of 0.2g were occasionally reported during the 2,000 and 4,000 ft. runs, usually near the edges of the up or downdraughts.

Run above cloud at 9,000 ft. Vertical motions were irregular and small and no bumpiness was noted. Temperature varied with distance by about the same amount as below cloud and seemed to have little correlation with the direction of the vertical motions.

Run in cloud. Short notes are given as the runs were carried out at 8,000 and 6,500 ft. only.

(a) Cloud structure. The cloud consisted of mixed small cumulus and stratocumulus about 3,000 ft. thick and presented no regular structure. Cloud tops were just below freezing level.

(b) Composition. The cloud consisted of water droplets some of which reached drizzle size. The droplet spectra were rather wider than usual and details of these are given in Table 14 and Fig. 16. The drizzle forming process in this cloud was almost certainly coalescence only. No rain or drizzle was observed outside the cloud. The droplet spectra again vary considerably in the horizontal which is presumably associated with different stages of the coalescence process in different cells.

(c) Vertical motions and turbulence. Up and downdraughts were small and random. Turbulence was infrequent and usually between 0.1 and 0.2g. At 8,000 ft. it was observed most at the southern edge of the clouds and at 5,500 ft. mostly at the northern edges.

(d) There were no measurements made of water content.

Table 14

Flight 7. 14/8/52.

Droplet distribution by volume

Droplet diameter "d"	Percentage of total by volume contained in droplets of diameter less than "d".					Height feet
	Sample 1	2	3	4	5	
μ						
11	0.2	0.1			0.1	8,000
17	5.0	7.8	1.2		5.4	
25	9.4	19.3	8.5		7.8	
35	19.7	44.0	33.2		12.2	
50	49.5	51.9	78.3		27.2	
70	68.8	69.8	86.9		37.2	
90	72.7	69.8	100.0		44.2	
110	79.3	100.0			56.4	
130	100.0				64.0	
150					69.6	
180					80.7	
220					100.0	

/11

Table 14 continued

Droplet diameter "d"	Percentage of total by volume contained in droplets of diameter less than "d"					Hei ht feet
	Sample 1	2	3	4	5	
μ						
11	0.1		0.1		0.1	6,500
17	0.1		0.1		0.1	
25	9.4	8.5	13.2		4.1	
35	31.3	26.1	31.6		15.1	
50	51.1	42.4	70.3		37.7	
70	66.7	69.9	82.9		87.8	
90	70.4	100.0	89.0		91.9	
110	70.4		93.6		100.0	
130	70.4		100.0			
150	70.4					
180	100.0					

Flight 8. 15/8/52.

1. Execution of the Flight. As the ground organisation of the project was being dispersed on this day, the more vigorous convection to the west - south-west of Farnborough was investigated. A cumulus congestus amongst several that had already become glaciated was selected for investigation after an aircraft sounding had been made to 20,000 ft. ICAN, but proved to be beyond the range of Farnborough Long Range Radar. Eventually a line of cumulus congestus, running east-west and comprising clouds of all sizes, was selected. Most of the cells were still growing and many had reached 15,000 - 20,000 ft. The growth cycle appeared to reach maturity in about 20 minutes.

Traverses were made through this cloud sheet on northerly and southerly headings at 2,000 ft. intervals from 19,000 to 9,000 ft. At the latter height the aircraft began to enter the radar ground echo of Farnborough Control and the investigation was abandoned. No clear air traverses below cloud were made.

The rotating disc icing meter was unserviceable on this flight and no quantitative icing observations are presented though airframe icing was reported at all levels down to 11,000 ft. in the cloud.

Cloud photographs are presented in Figs. 18a and b.

2. The soundings and their relation to observed cloud features. The results of the sounding have been plotted in Fig. 17. Considering this diagram:-

(a) From parcel method calculations the lowest condensation level would be at about 950 mb., rising later to 905 mb., relative to a corrected surface pressure of 1013 mb., with a surface temperature of about 68°F and dewpoint of 59°F.

The lowest condensation level was at about 945 mb. and this appears to have been a general value.

A second condensation level was observed at 820 mb. Just below this height there was considerable conditional instability and above there was moderate wind shear; both of these factors are presumably of importance in the formation of the stratocumulus layer observed between 820 and about 750 mb. Above 700 mb. there was considerable drying and a marked decrease in shear.

Although entrainment did not inhibit the growth of vigorous cumulus clouds the values of water content measured within them indicates that it must have been a factor of importance.

/(b)

(b) By similar calculations tops would be limited locally to 920 mb. with another stop at 670 mb. - this latter "stop" being reinforced by the marked drying at 700 mb. The marked instability throughout the ascent on this day would permit some cloud to develop far beyond 450 mb. in the absence of any great amount of entrainment.

Observed tops were all about 895 mb. for the lowest stratocumulus layer, about 750 mb. for the other stratocumulus layer, and generally 700 to 530 mb. for cumulus, although some clouds far to the south had anvils above 300 mb.

The fact that many cumulus developed into the very dry environment above 700 mb. indicates that again entrainment is of little importance in the higher portions of convective clouds at least especially where there is marked instability.

3. Results of the traverses. The main features are shown in Table 15 and short notes are also given below:-

(a) Cloud structure. The cloud investigated was the most easterly of a line of similar clouds lying east-west. The investigation comprised a series of traverses on northerly and southerly headings. A single cell was found at both upper and lower levels though two cells were found at 11,000 and 13,000 ft. Cell size was about 1-2 miles.

(b) Cloud composition. It is interesting that although this cloud had reached a temperature of +6°F in its upper regions, no ice crystals had appeared: it is usually expected that crystal formation would commence at temperatures of the order of +12°F. With large cumulonimbus clouds in the area there must have been a plentiful supply of ice crystal nuclei.

Although crystals had not appeared it was apparent that the cloud was approaching maturity since a downdraught was setting in in the upper levels.

The detailed droplet spectrum is presented in Table 16 and Fig. 19. It is notable that the spectrum varied considerably in the horizontal over distances as short as 200 yd. and also in the vertical. A few very large drops were reported at 17,000 and 15,000 ft. It is apparent from the spectra that the coalescence process was considerably advanced and that any rain production later would be due to a complicated mixture of crystal and coalescence processes.

(c) Vertical currents and turbulence. Although vertical motions over much of the cloud were less than 10 ft./sec. vertical motions of the order of 20 ft./sec. averaged over half a mile were by no means uncommon at all levels.

The strength of these vertical motions must presumably be associated with the large positive area evident on the tephigram of this ascent. To the strength of these currents may also be ascribed the persistence of supercooled drops at the abnormally low temperature previously mentioned.

The cloud and its environment appears to contain regularly arranged broad ascending and descending currents of air of lateral dimension 5 miles each having at its centre a core of lateral dimension about 2 miles moving in opposite sense to its environment. The cloud examined was set half in an ascending current and half in a descending one with the descending core of the broad ascending current beginning to encroach into the broad, descending current at the top of the cloud.

/Turbulence

Turbulence was found normally in the shear zone between vertical motions of opposing sense. It was observed at all levels below 19,000 ft. and was usually greater than 0.2g. Turbulence estimated to be 0.7g - the highest observed during 1952 by the Meteorological Research Flight - was observed at both 15,000 and 13,000 ft.

(d) Water content. Water content was normally greater than 0.2g/m^3 and occasionally exceeded 1.6g/m^3 (the limitation of the instrument). It appeared to reach a minimum at 13,000 ft.

(e) Temperature in cloud. Temperature in cloud, though somewhat suspect for reasons previously mentioned, appeared to be quite variable, being higher in updraught and lower in downdraught regions. The temperature differential between these areas was often about 1-2°F and the maxima appeared to coincide with maxima in water content.

(f) Run above cloud at 19,000 ft. Temperature rose gradually from about -7°F to -3°F during this run, the lower temperatures apparently being associated with downdraught areas and the higher with updraughts.

Vertical motions were usually less than 5 ft./sec. but a downdraught was observed above cloud of about 20 ft./sec.

Table 15.

Main cloud features of cumulus congestus investigated in Flight 8.

Cloud Traverses

Height feet	Mean Temp. °F.	Turbulence Max g	Turbulence Mean g	Icing Max g/cu.m.	Icing Mean g/cu.m.	Water Content Max g/cu.m.	Water Content Mean g/cu.m.	Extent miles	No. of cells	Remarks - composition
17,000	+6	.3	.2	Meter u/s but ice observed on aircraft.		>1.6	-	2	1	Water droplets up to 80μ diameter.
15,000	+12	.7	.3	"		>1.6	.7	3	1	Water droplets up to 120 μ diam. occasionally 200-300 μ.
13,000	+23	.7	.3	"		.6	.3	3	2	Water droplets up to 60 μ diameter.
11,000	+27	.4	.2	-		>1.6	.3	4	2	Water droplets up to 100 μ diameter.
9,000	+36	.3	.2	-		1.0	.6	3	1	Water droplets up to 100 μ diameter.

Lower levels not investigated. Base was probably about 3,000 ft.

/Table 16

Table 16

Flight 8

Droplet distribution by volume

Droplet diameter "d"	Percentage of total by volume contained in droplets of diameter less than "d"					Height feet
	Sample 1	2	3	4	5	
μ						
11	0.1			0.1		17,000
17	0.1			0.1		
25	6.4			4.1		
35	13.9			4.1		
50	38.8			25.7		
70	85.7			39.0		
90	100.0			46.8		
110				46.8		
130				100.0		
Other sizes			1 drop 500 μ			
11	0.1	0.1				15,000
17	0.1	0.1				
25	3.0	1.6	0.4	2.5		
35	5.0	5.3	0.4	2.5		
50	13.0	17.9	2.1	12.2		
70	30.1	47.3	4.1	21.6		
90	57.0	66.3	7.3	43.8		
110	57.0	88.6	7.3	43.8		
130	57.0	100.0	10.0	100.0		
150	57.0		10.0			
180	100.0		28.7			
220			28.7			
260			49.9			
300			100.0			
Other sizes	1 drop 1,300 μ				1 drop 500μ	
11	0.2	0.1	0.4	0.1		13,000
17	0.2	0.1	0.4	0.1		
25	40.0	62.4	34.5	20.3		
35	94.7	95.4	56.1	69.4		
50	100.0	100.0	61.7	86.5		
70			100.0	91.7		
90				91.7		
110				100.0		
11	0.1				0.5	11,000
17	0.1				0.5	
25	20.5			6.3	5.7	
35	71.1			21.0	36.3	
50	71.9			37.4	66.6	
70	82.9			77.3	100.0	
90	82.9			87.6		
110	100.0			100.0		

/11

Table 16 continued

Droplet diameter "d"	Percentage of total by volume contained in droplets of diameter less than "d"					Height feet
	Sample 1	2	3	4	5	
μ						
11	1.1					9,000
17	1.1					
25	7.9			3.7		
35	13.7			3.7		
50	24.2			26.9		
70	35.1			63.5		
90	41.5			63.5		
110	47.8			63.5		
130	69.6			100.0		
150	87.0					
180	87.0					
220	100.0					

M.R.P. 826

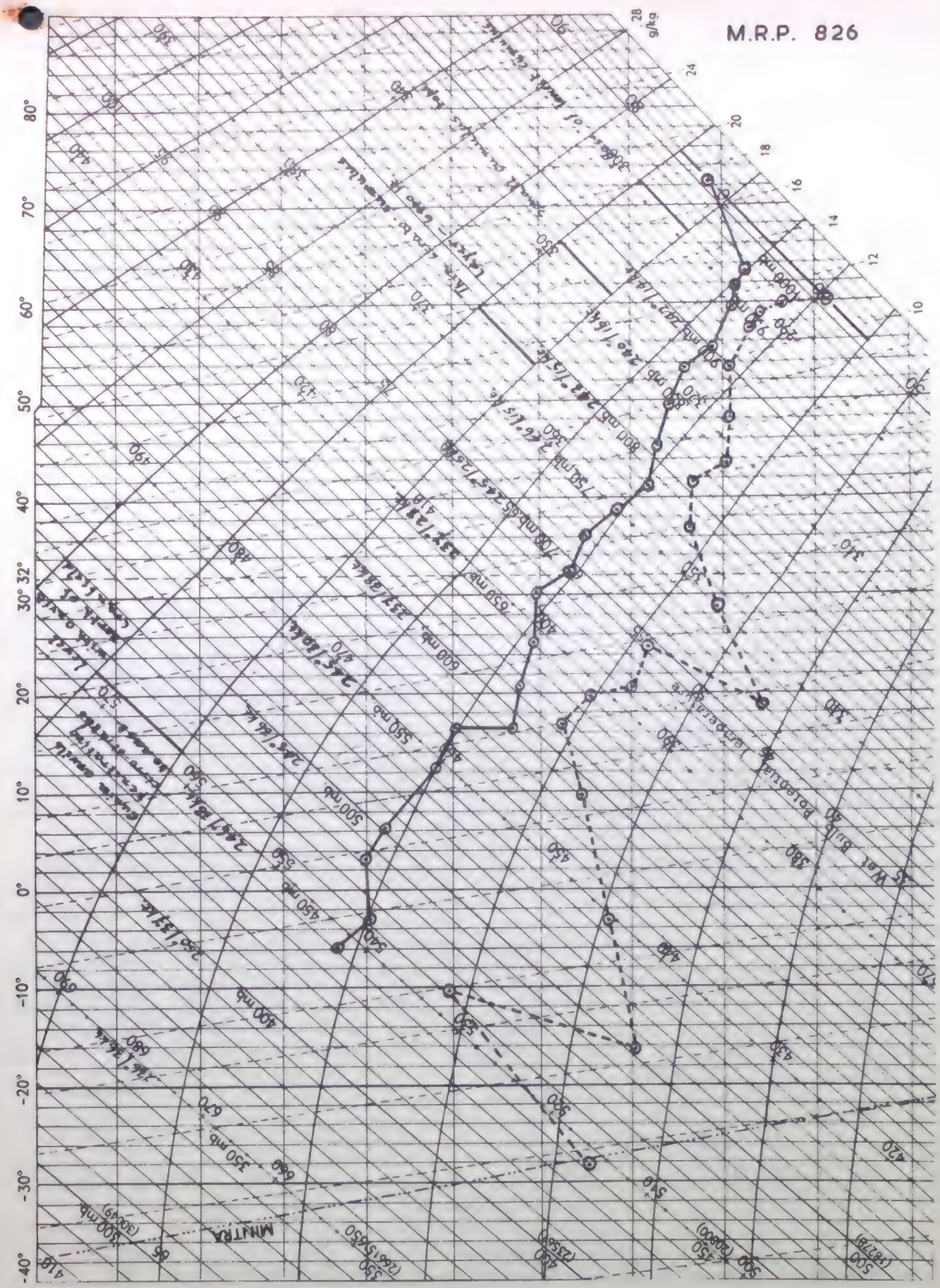


Fig. 1 Hastings ascent northwards from Cranfield on 5.8.'52 at about 16.00 Z.

Flight 1. Figs. 2a and b

M.R.P. 826

Fig. 2a Lenticular strato-cumulus at 6800 ft. amongst lower cumulus tops.

Fig. 2b Cloud investigated, aircraft at 22000 ft. and approaching from North

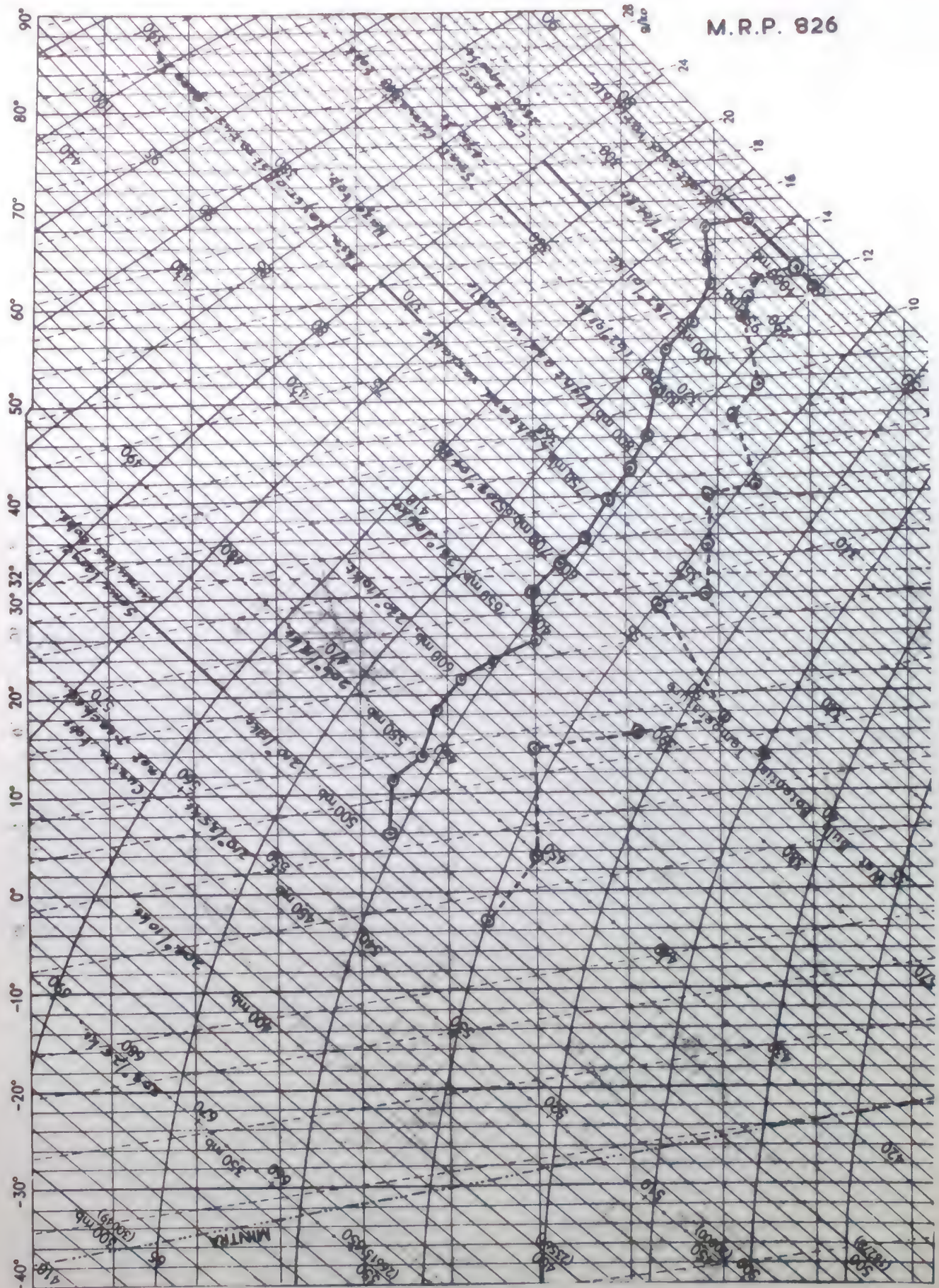


Fig. 3 Hastings ascent over Cranfield on 6.8.62 at about 14.00Z

M.R.P. 826

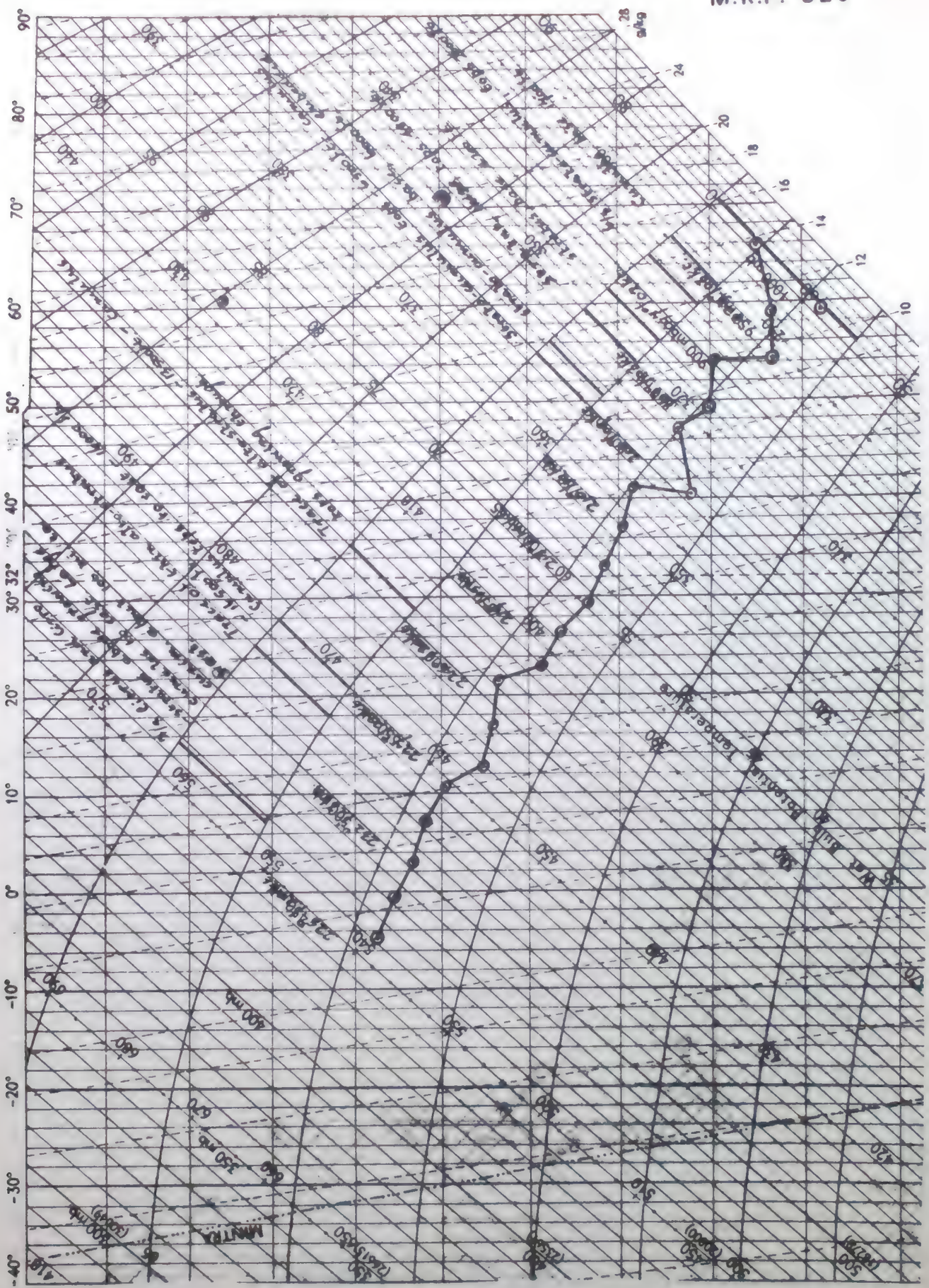


Fig. 3a Mosquito ascent over Cranfield on 6-8-62 at about 2002.

Flight 2. Figs. 4a and b.

M.R.P. 826

Fig. 4a. Developing cumulus from 7500 ft. overshadowed by anvil of Fig. 4b.

Fig. 4b. Part of distant, glaciated, cumulo-nimbus top above 25000 ft.

Slight 2. Figs. 4c and 4d.

M.R.P. 826

← Strato-cumulus layer at 760 mb.

Fig. 4c. Developing cumulus from 7000 ft.

Fig. 4d. Developing Cumulus from 5000 ft.

M.R.P. 826

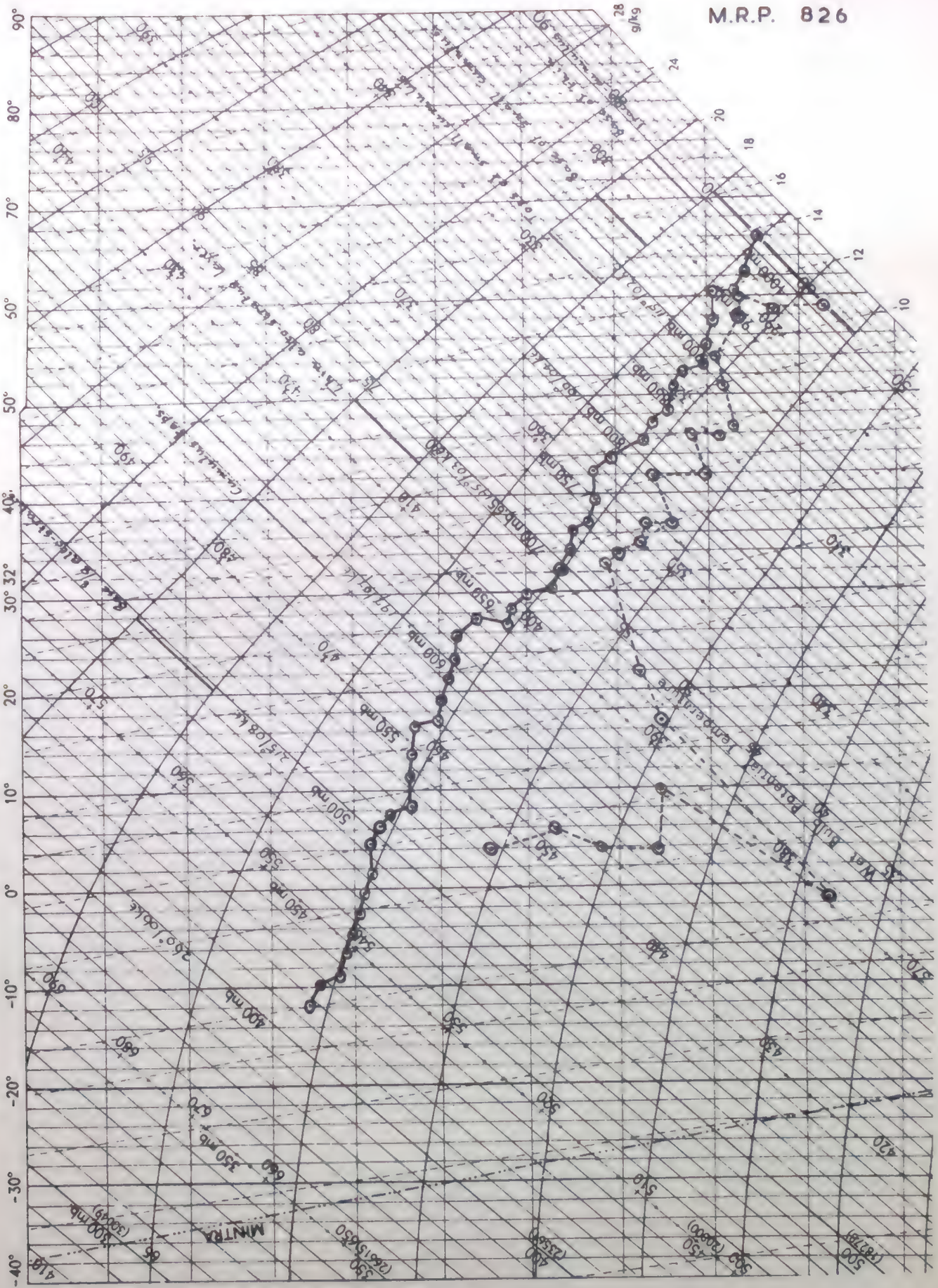


Fig. 5 Hastings ascent over Cranfield on 7·8·52 at about 11·30 Z.

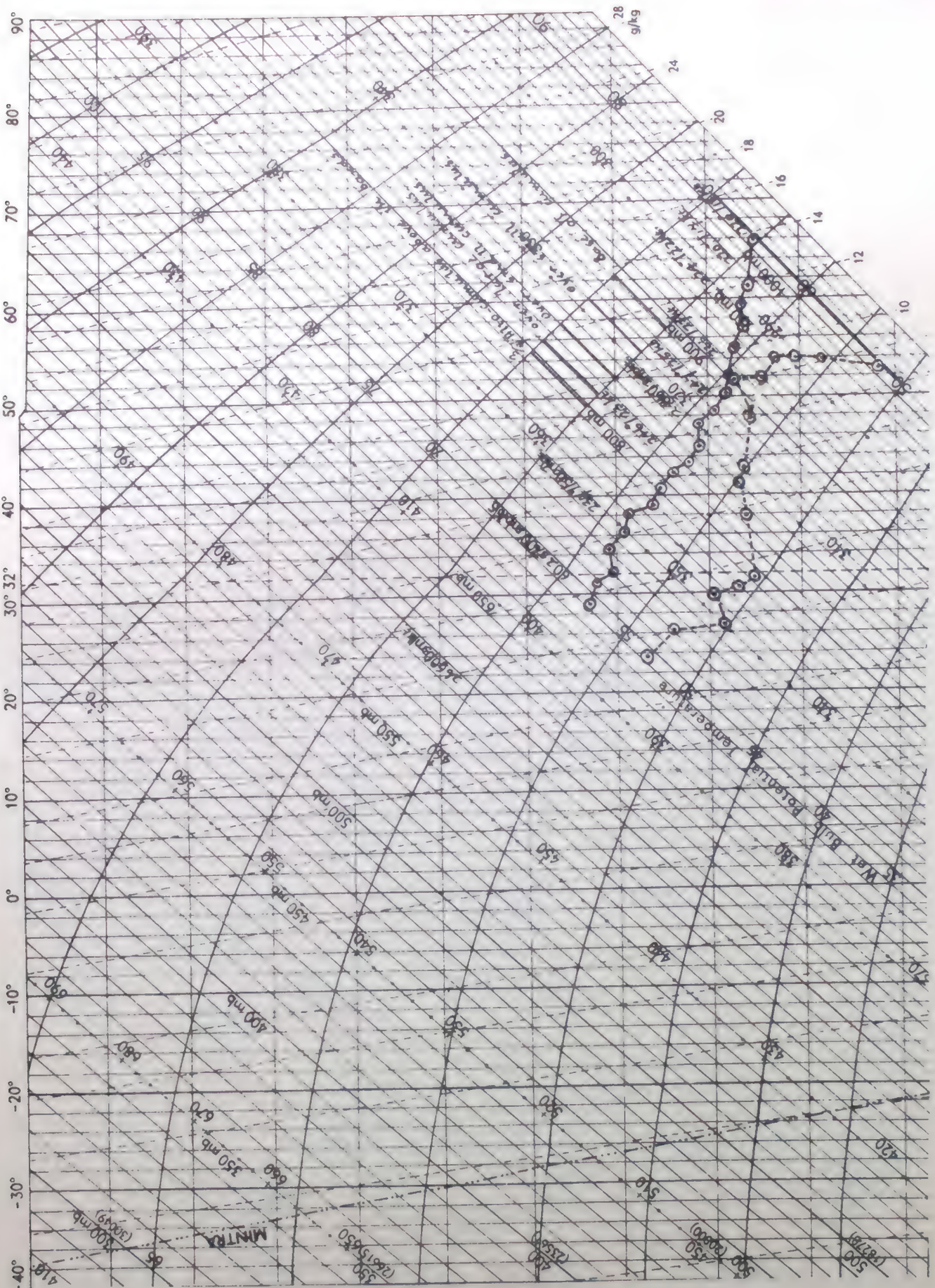


Fig. 6 Hastings ascent northwards from Farnborough on 8.8.62 at about 11.30 Z.

Flight 4. Figs. 7a and b.

M.R.P. 826

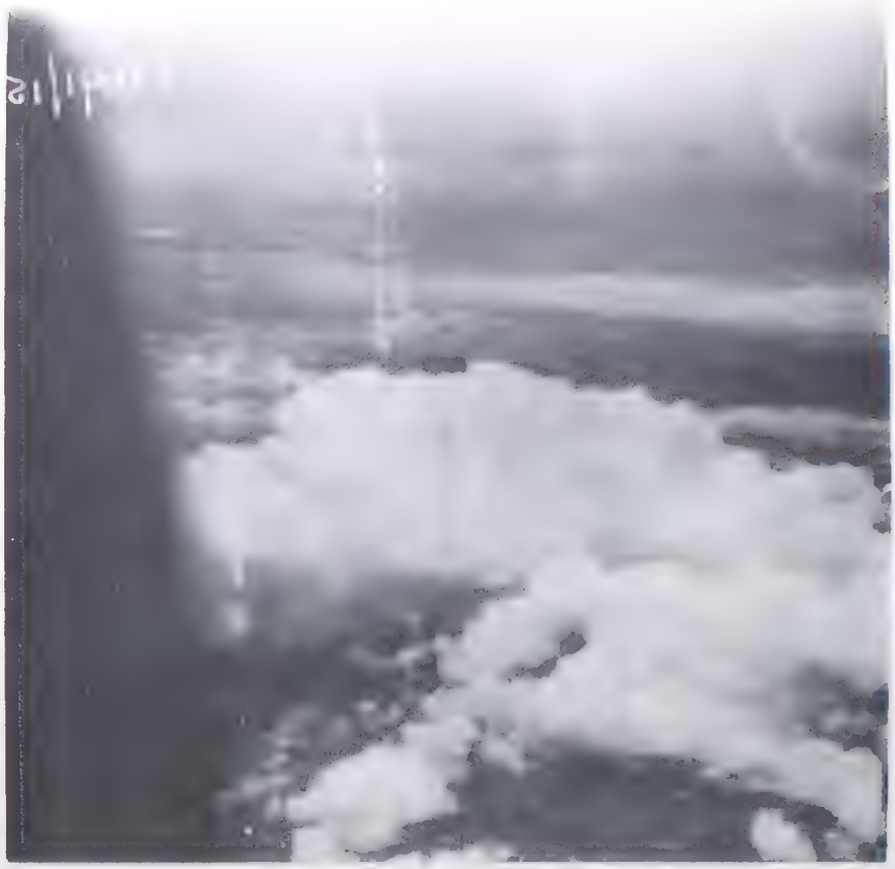


Fig. 7a. Complex investigated, viewed from 9000 ft. and probably from South

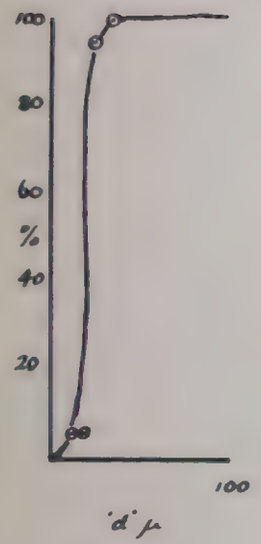
Fig. 7b. General view of cloud in area, complex of Fig. 7a on left.

Fig. 8 Droplet distribution by volume – Flight 4

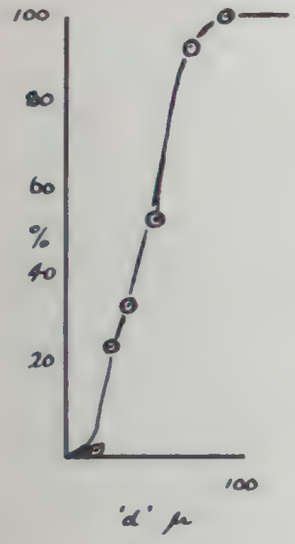
M.R.P. 826

4500' – Samples 1 and 2 in Northern minor cloud, sample 5 in northern major cloud.

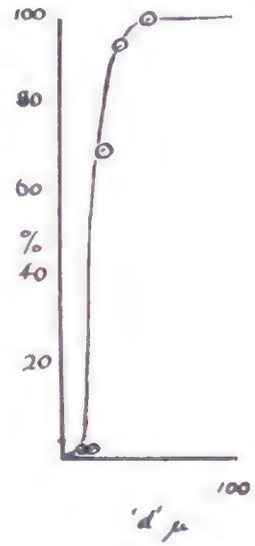
5000' – Samples 1–4 in southern main cloud, sample 5 in rain near its edge.



Sample 1

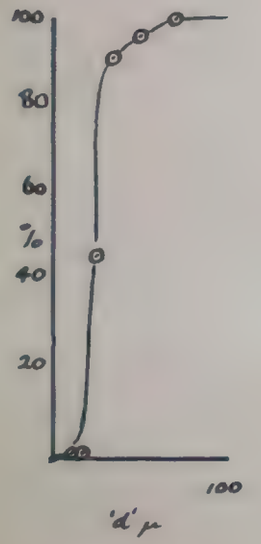


Sample 2

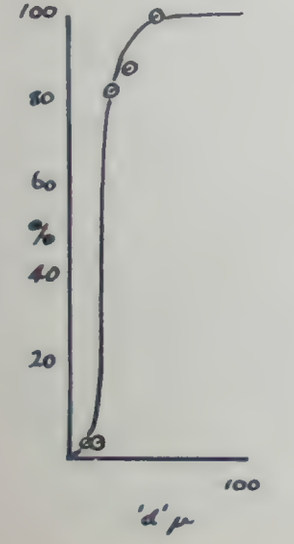


Sample 5

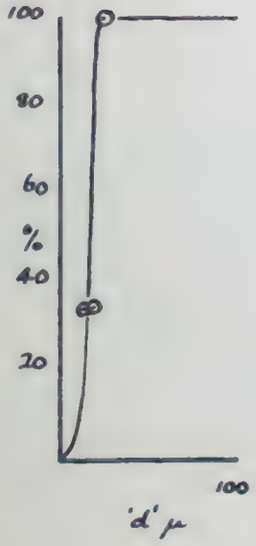
4500'



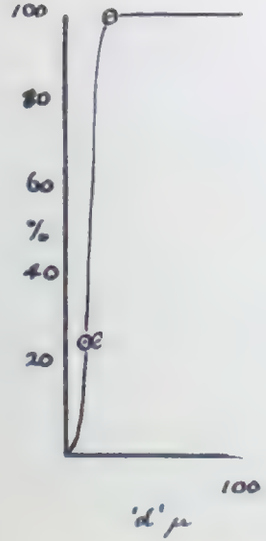
Sample 1



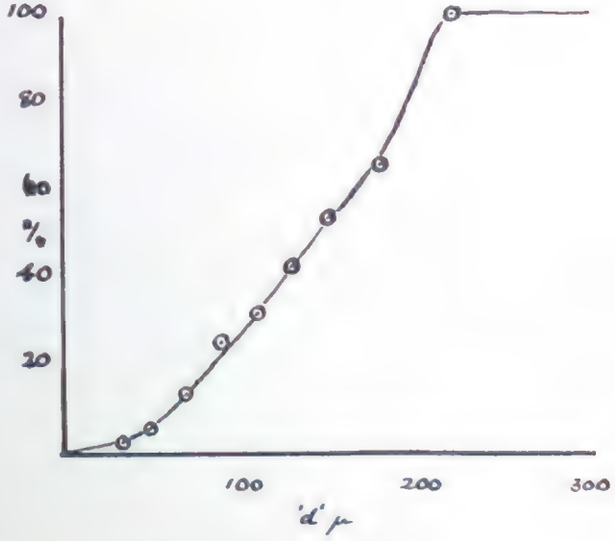
Sample 2



Sample 3



Sample 4



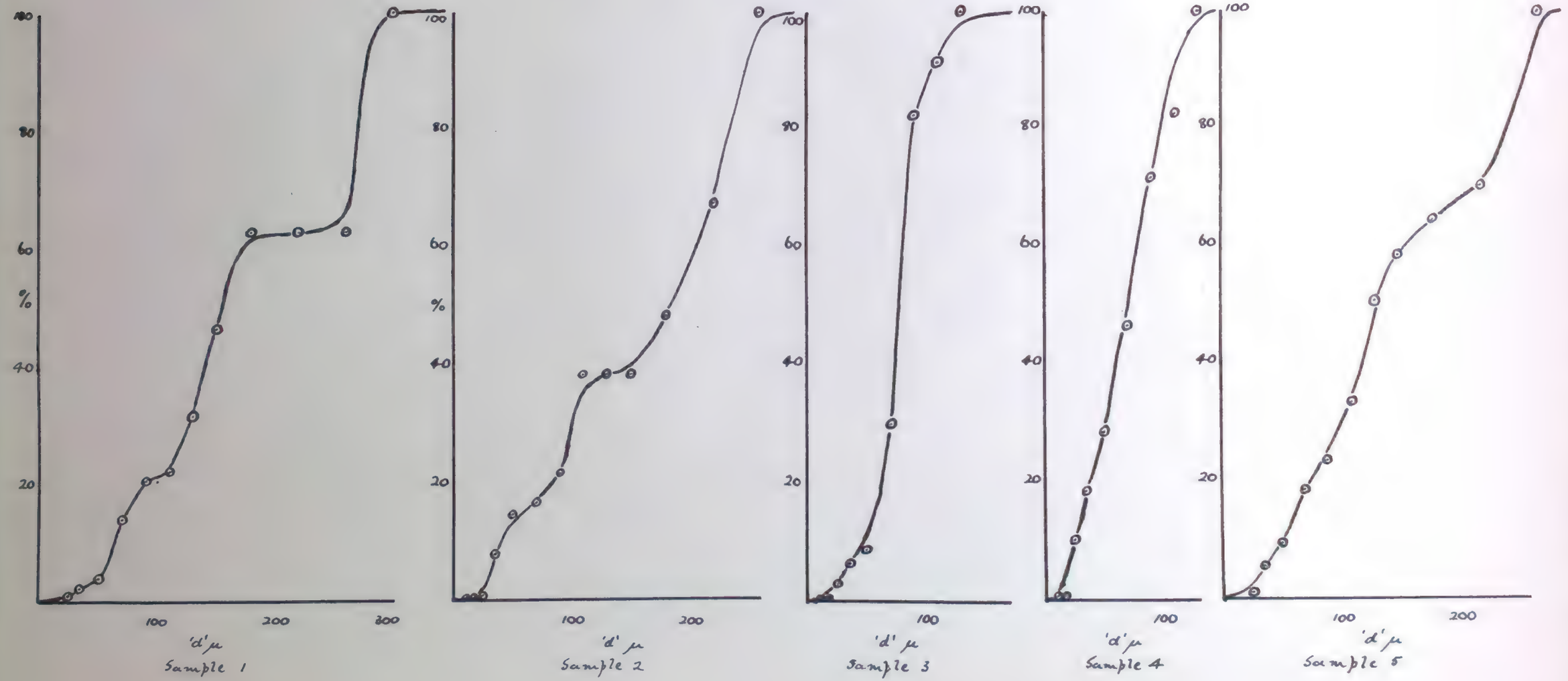
Sample 5

5000'

Fig. 8 (contd.) Droplet distribution by volume - Flight 4

M.R.P. 826

Samples in rain below and close to cloud base.



M.R.P. 826

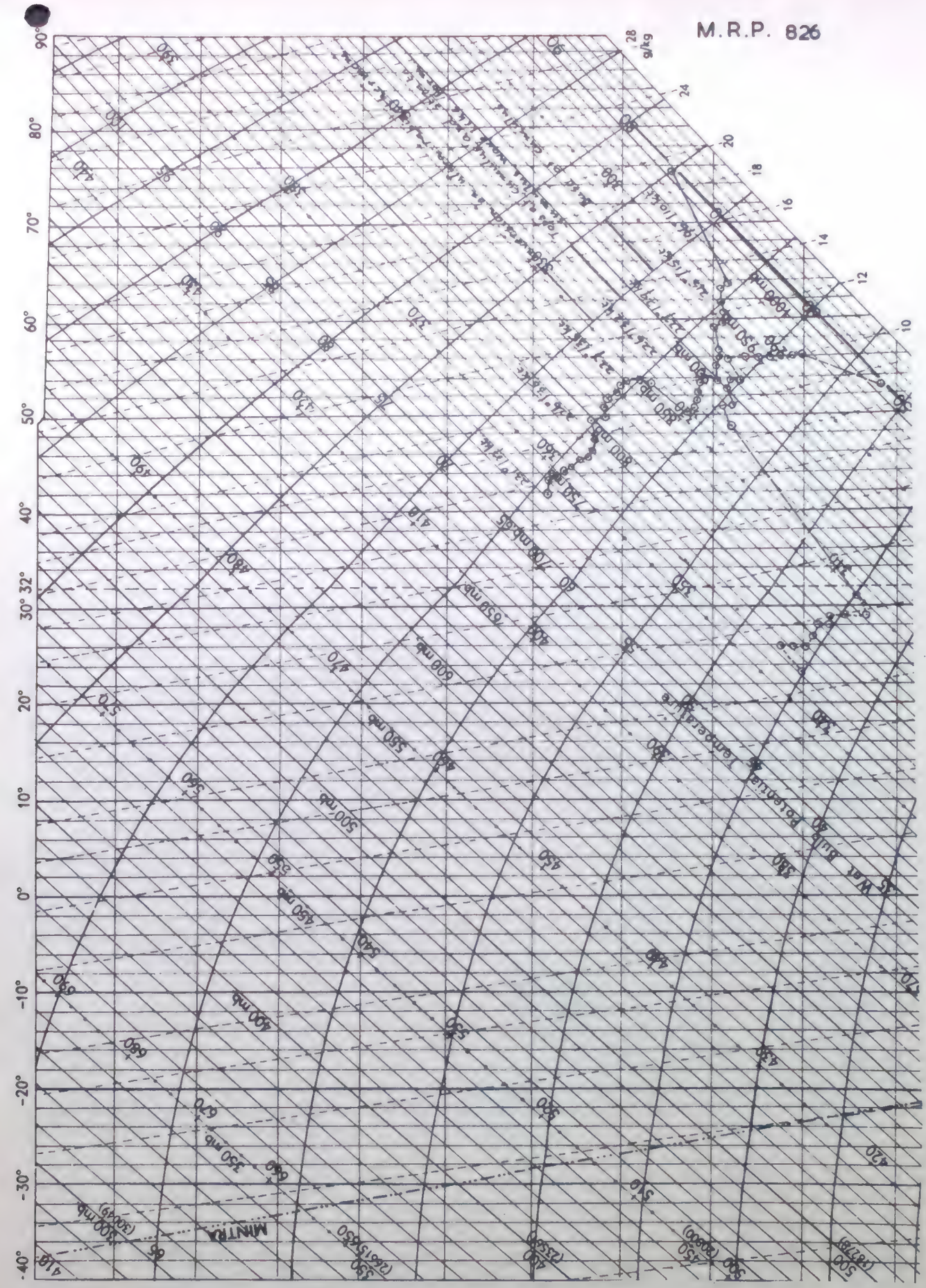


Fig. 9 Hastings ascent over Cranfield on 12.8.52 at about 1100 Z.

M.R.P. 826

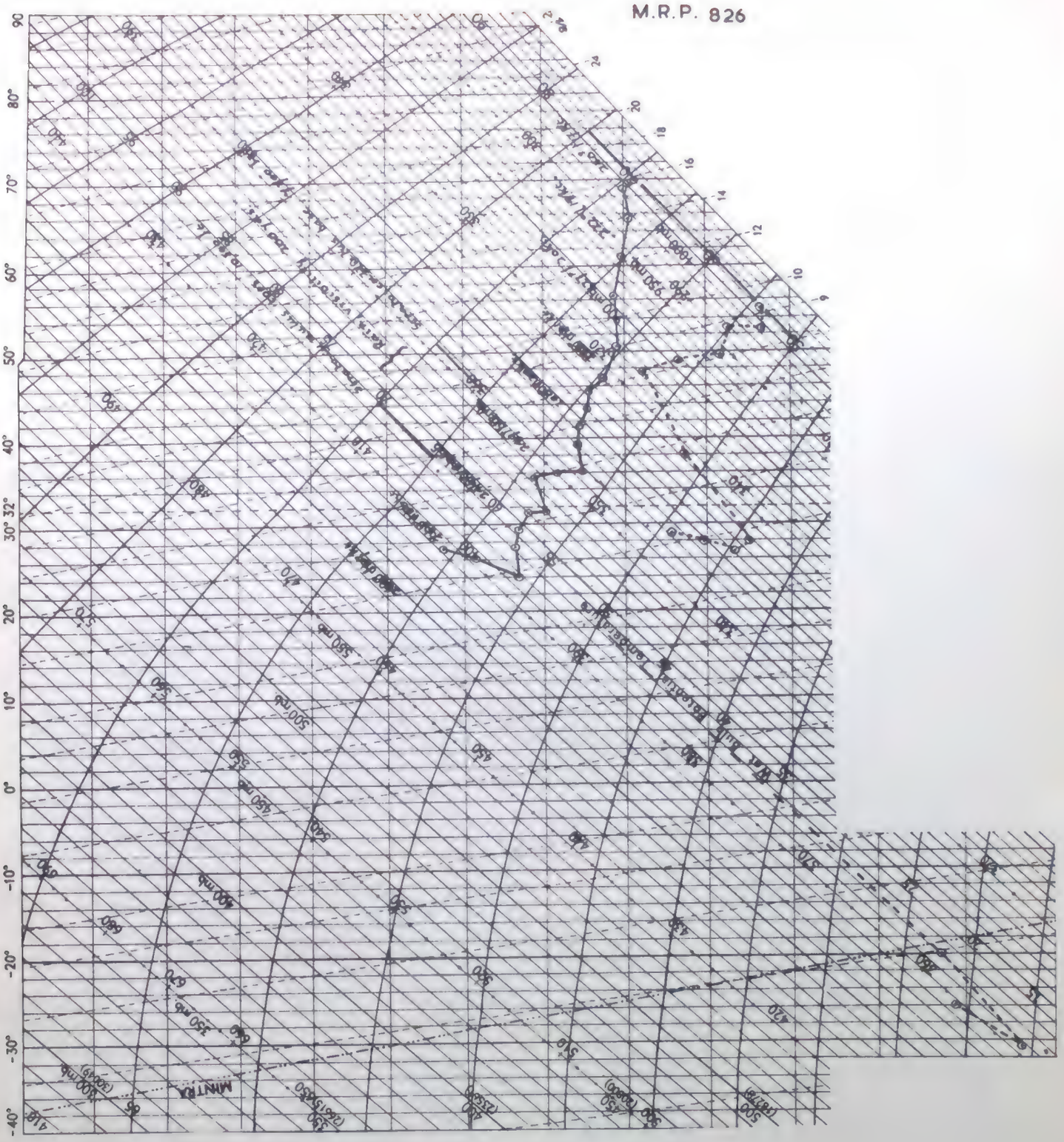


Fig.10 Hastings ascent over Cranfield on 13.8.52 at about 1500Z.

Flight 6 – Figs. 11a and b

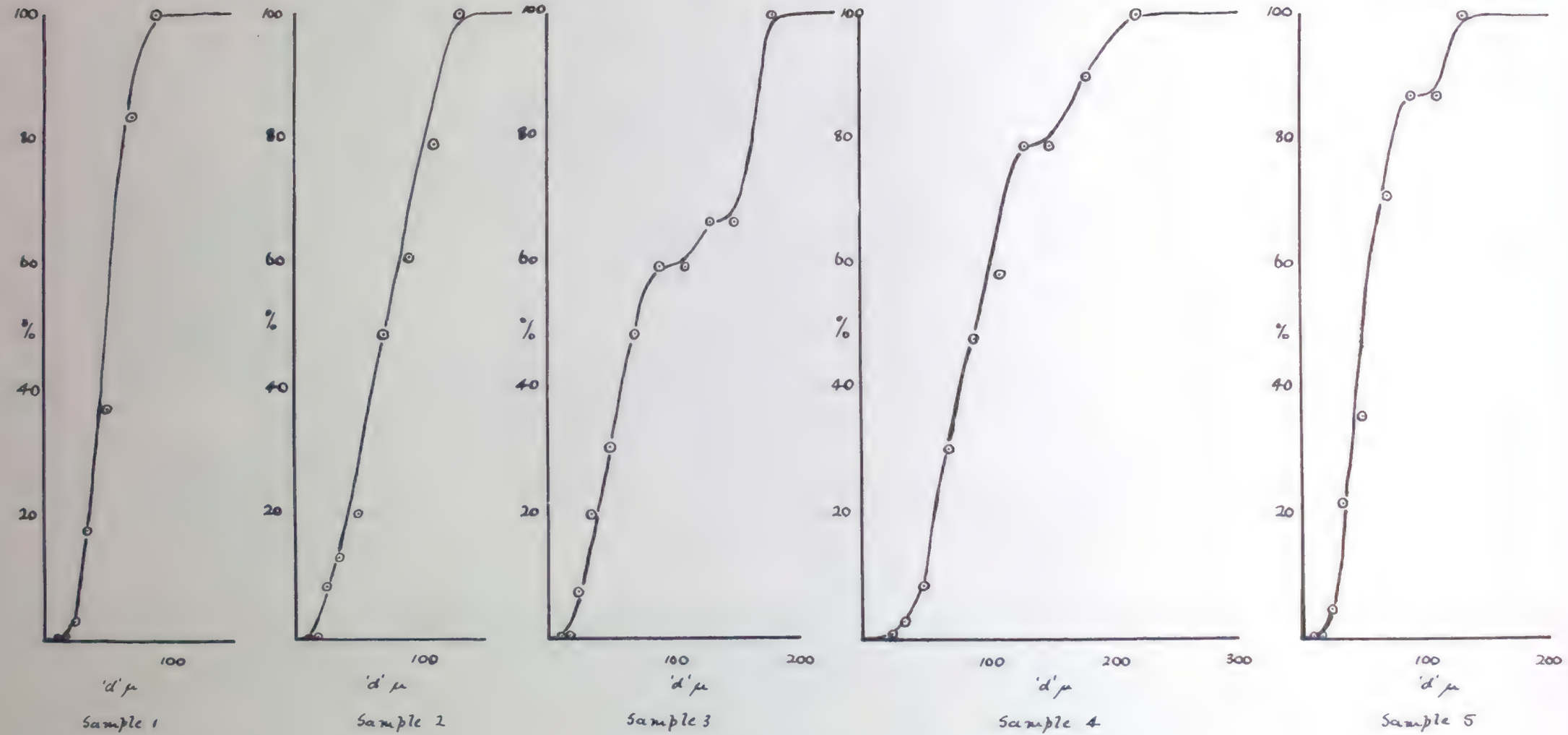
M.R.P. 826

Fig. 11a. Cumulus penetrating strato-cumulus sheet.

Fig. 11b General view of cloud sheet investigated.

Fig. 12 Droplet distribution by volume - Flight 6

M.R.P 826



Basic sample separation 200 yd.

8000'

Flight 6 - Figs. 13a. and 13b.

M.R.P. 826

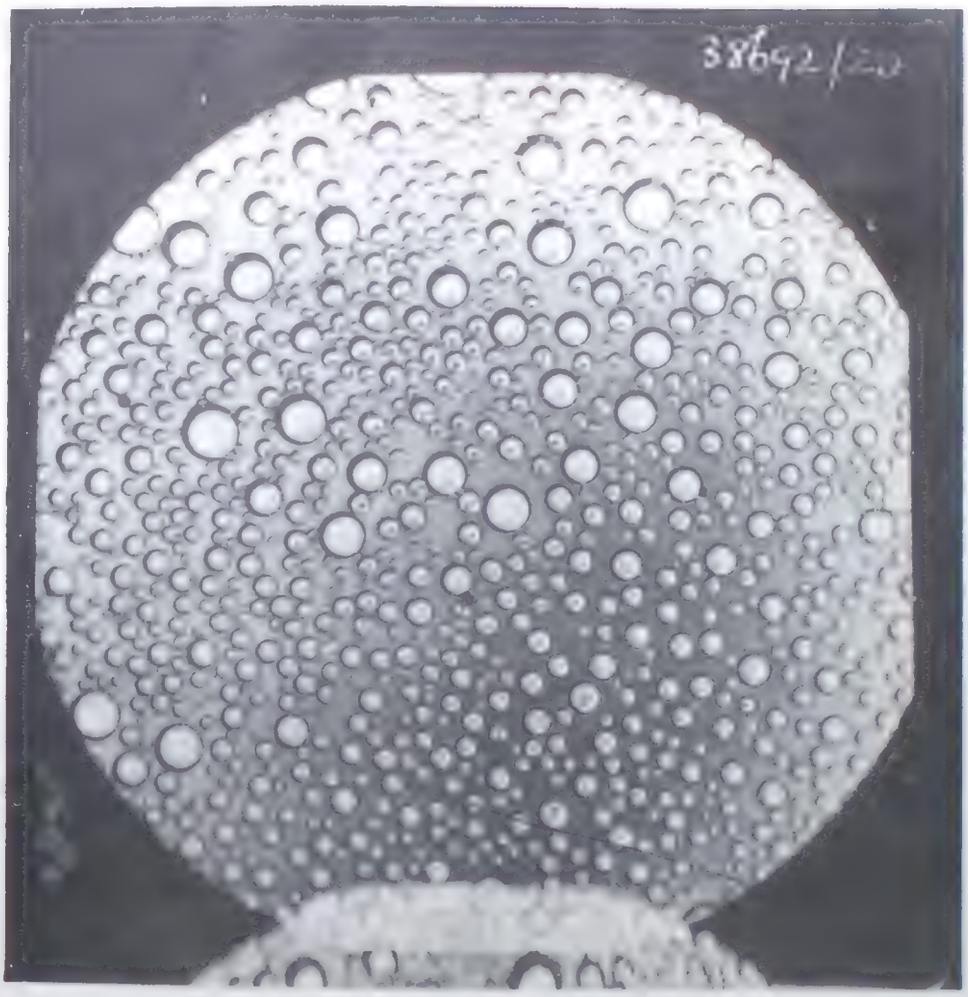


Fig. 13a.

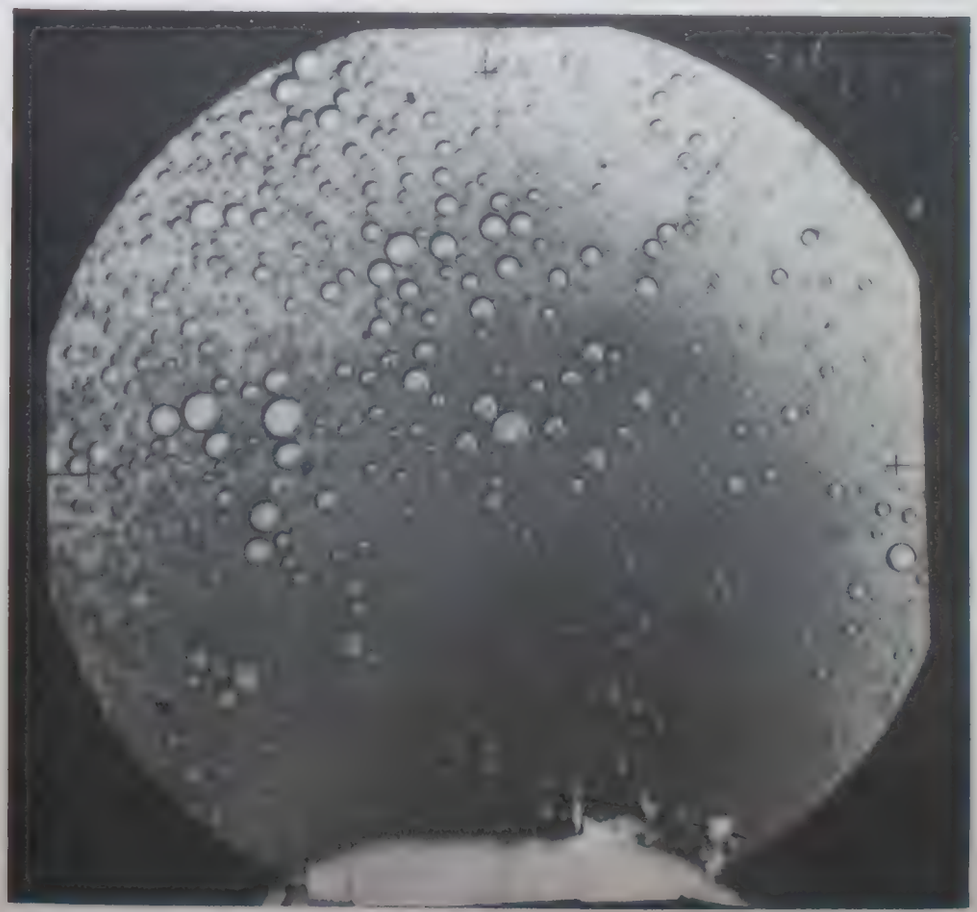


Fig. 13b. Typical examples of droplet samples

M.R.P. 8 26

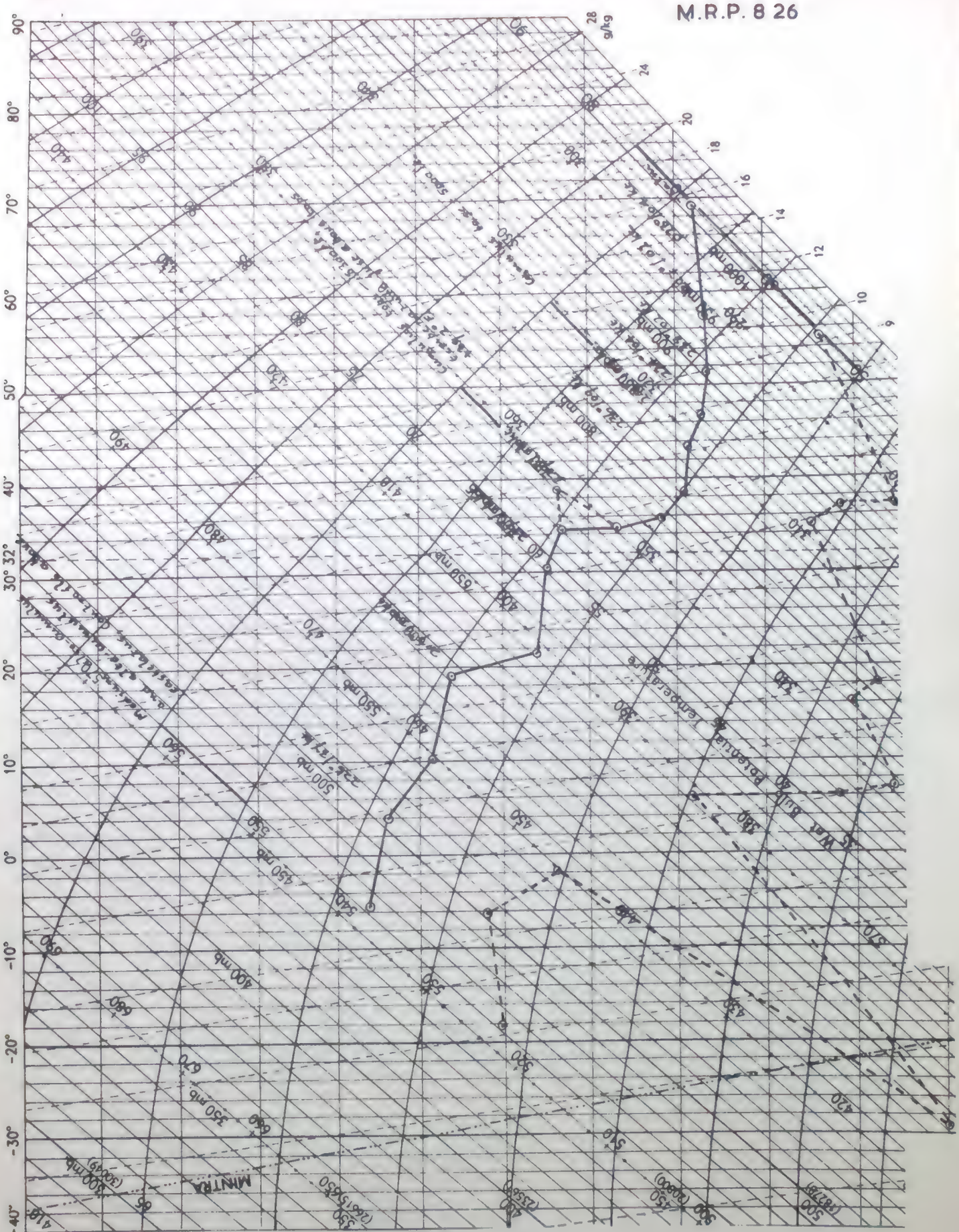


Fig. 14 Mosquito ascent over Cranfield on 14·8·52 at about 10·00 Z.

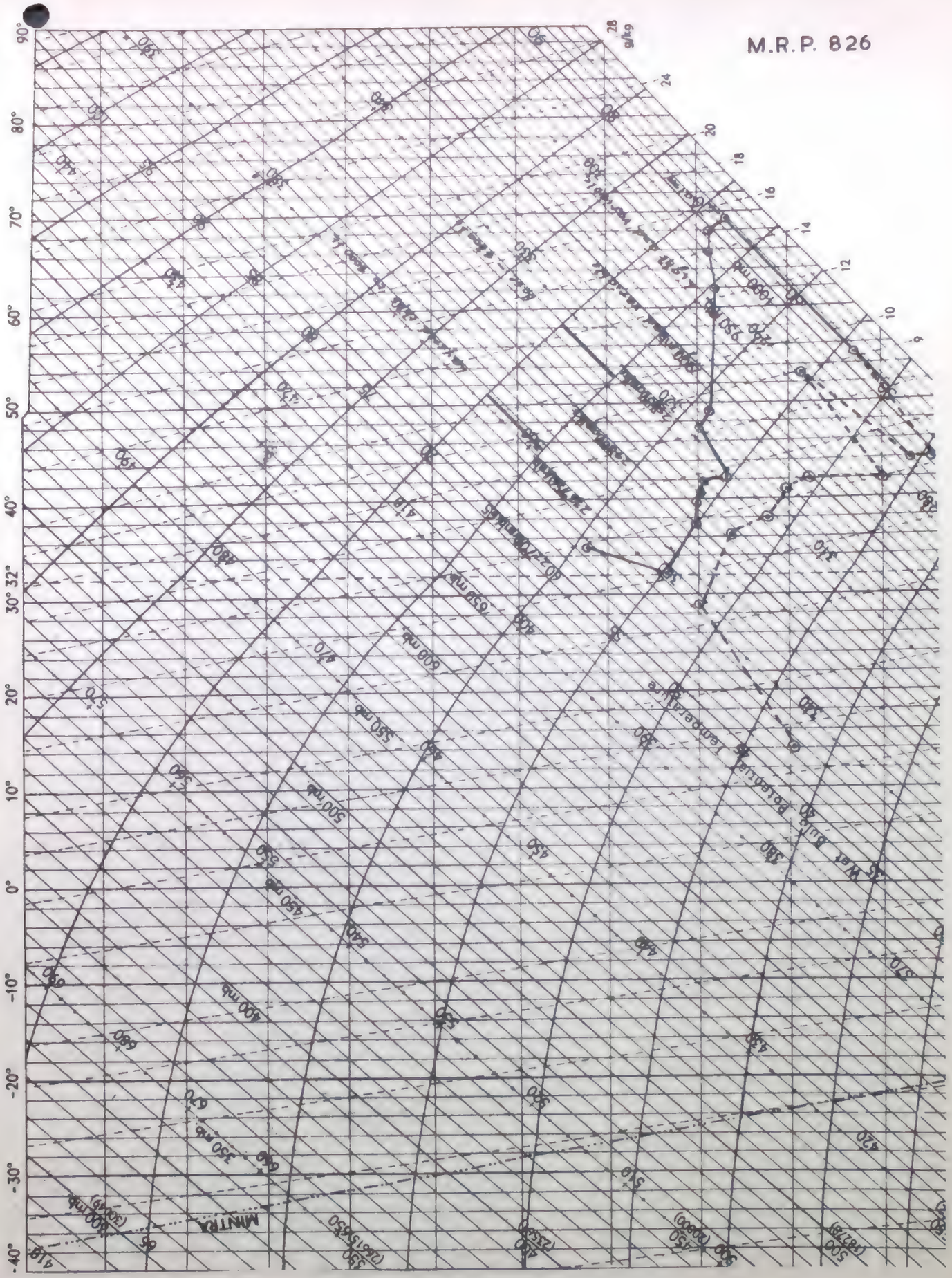
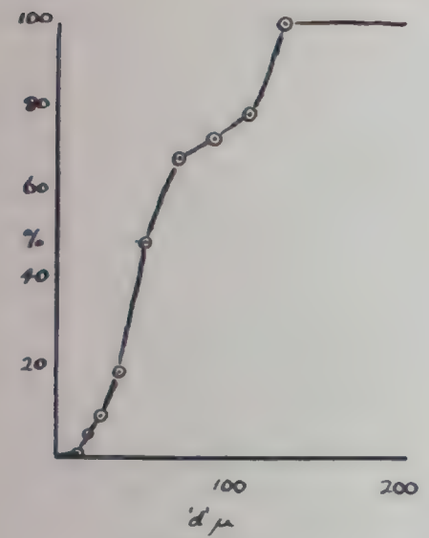
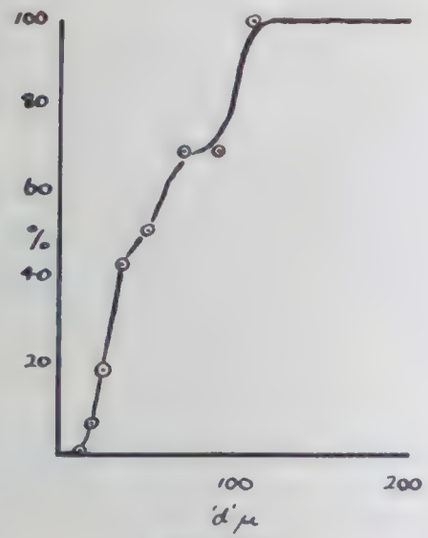


Fig. 15 Hastings ascent over Cranfield on 14.8.52 at about 1500Z.

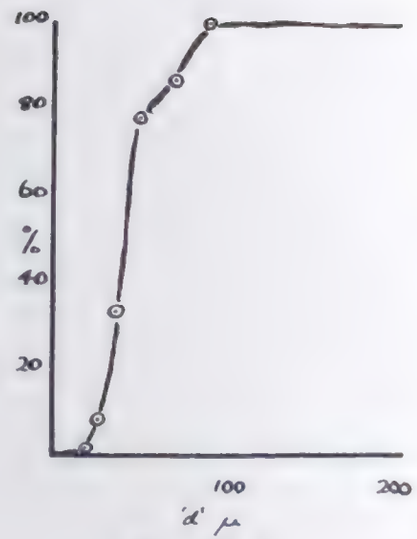
Fig. 16 Droplet distribution by volume – Flight 7



Sample 1

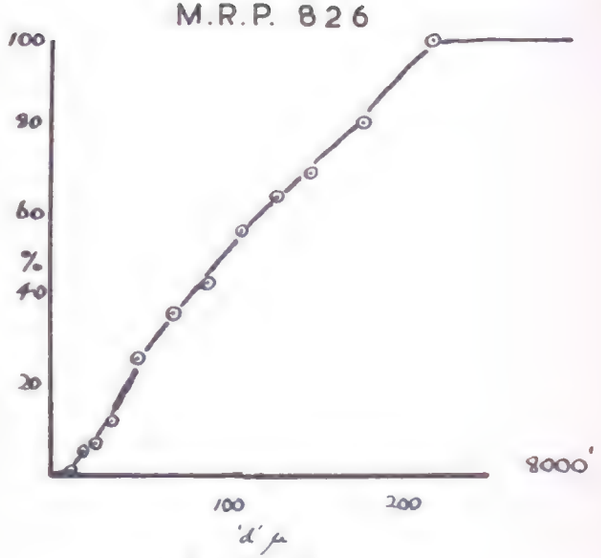


Sample 2

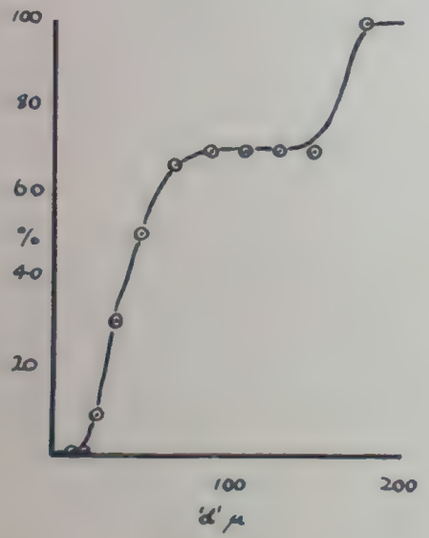


Sample 3

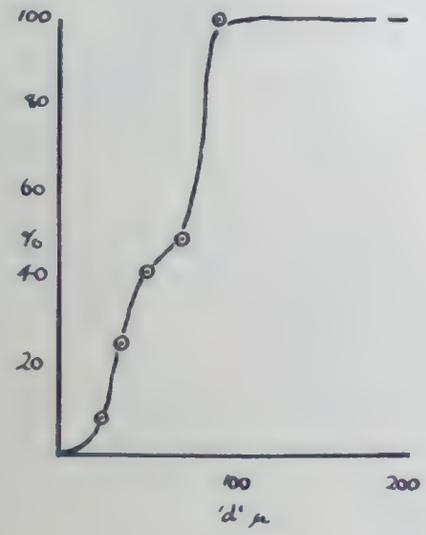
M.R.P. 826



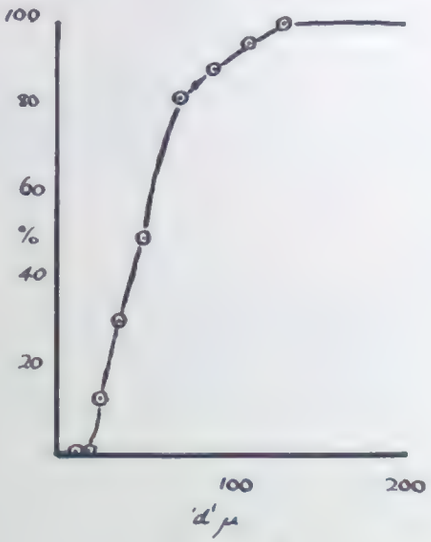
Sample 5



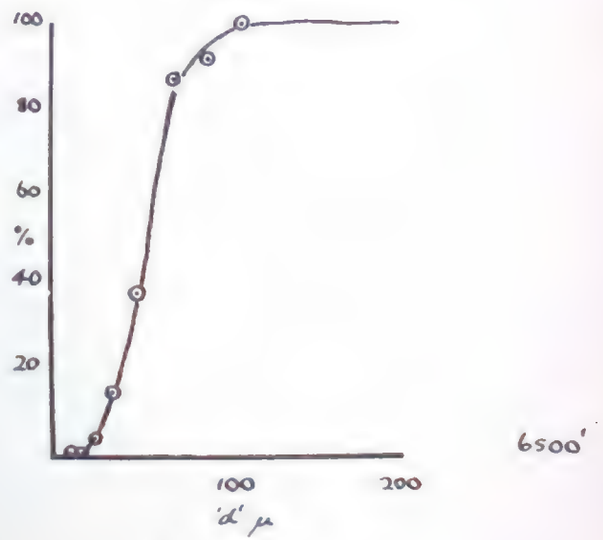
Sample 1



Sample 2



Sample 3



Sample 5

M.R.P. 826

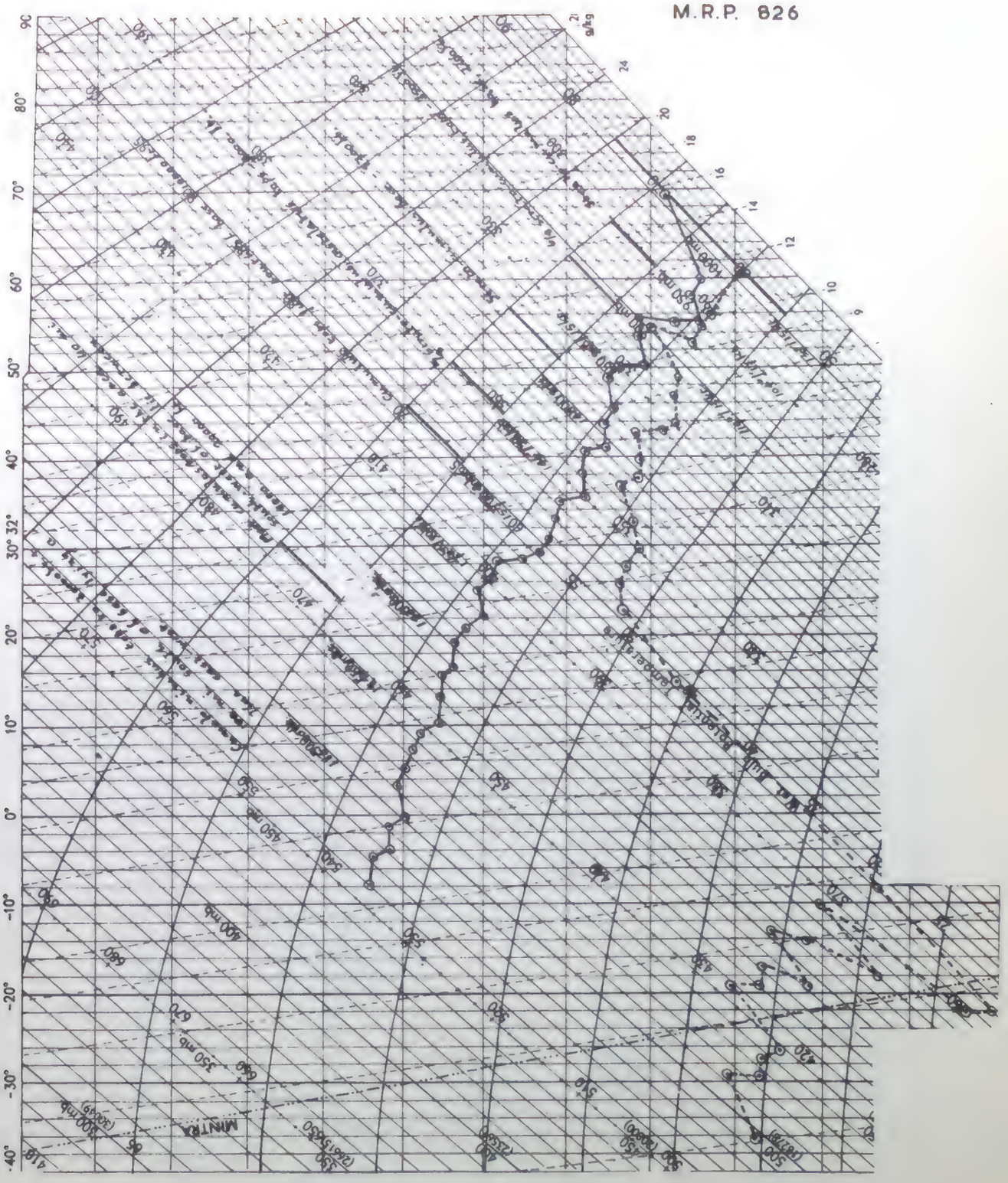


Fig. 17. Ascent in Hastings heading south-westerly from base on 16.8.'52 about 1400 Z.

Flight 8 - Figs. 18a and b.

M.R.P. 826

Fig. 18a. Cumulo-nimbus cloud originally chosen, anvil at about 30000 ft.

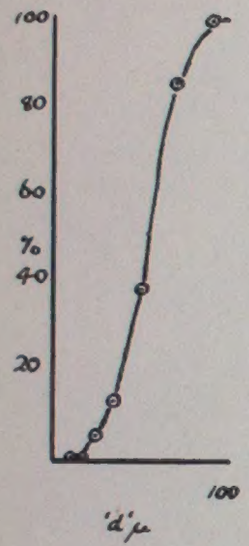
Fig. 18b. Cloud investigated, top at about 18000 ft.

M.R.P. 826

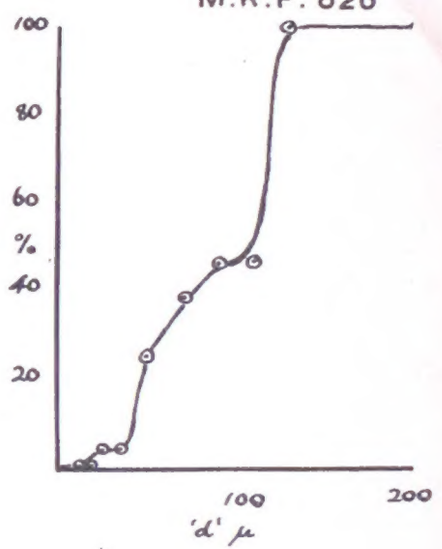
Fig. 19 Droplet distribution by volume - Flight 8

Basic sample seperation about 200 yd.

17,000'

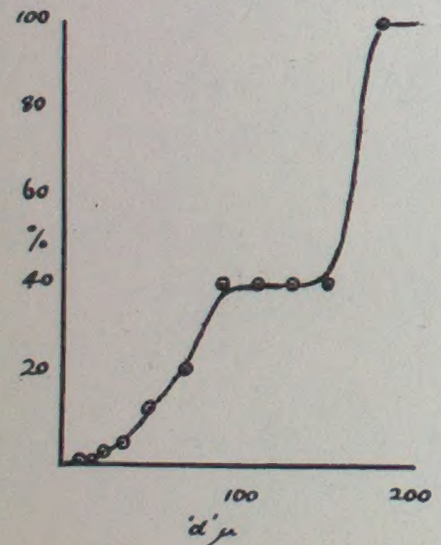


Sample 1

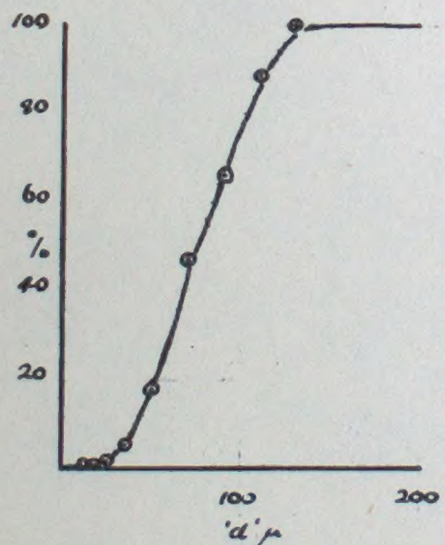


Sample 4

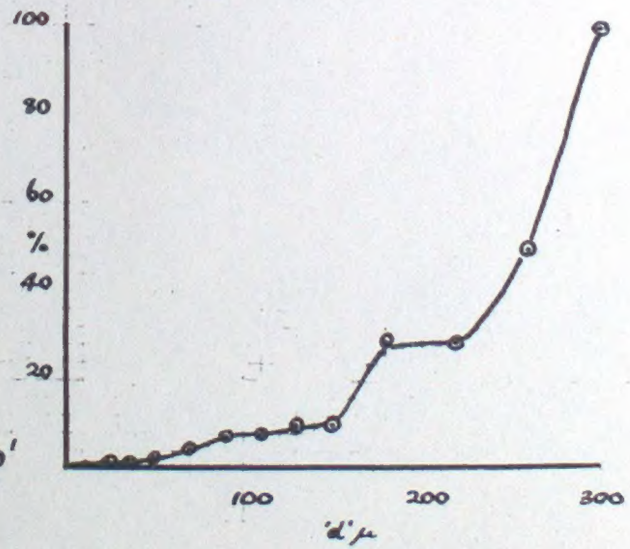
15,000'



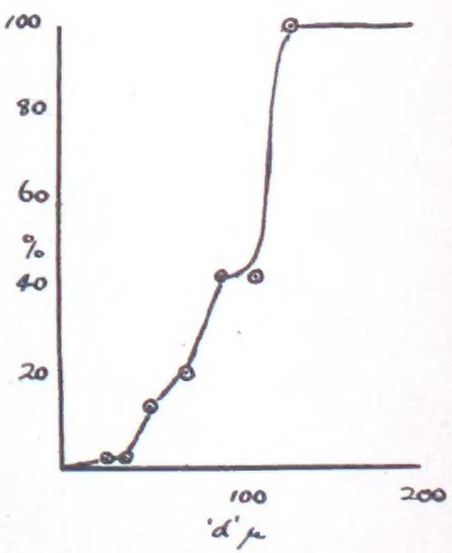
Sample 1



Sample 2

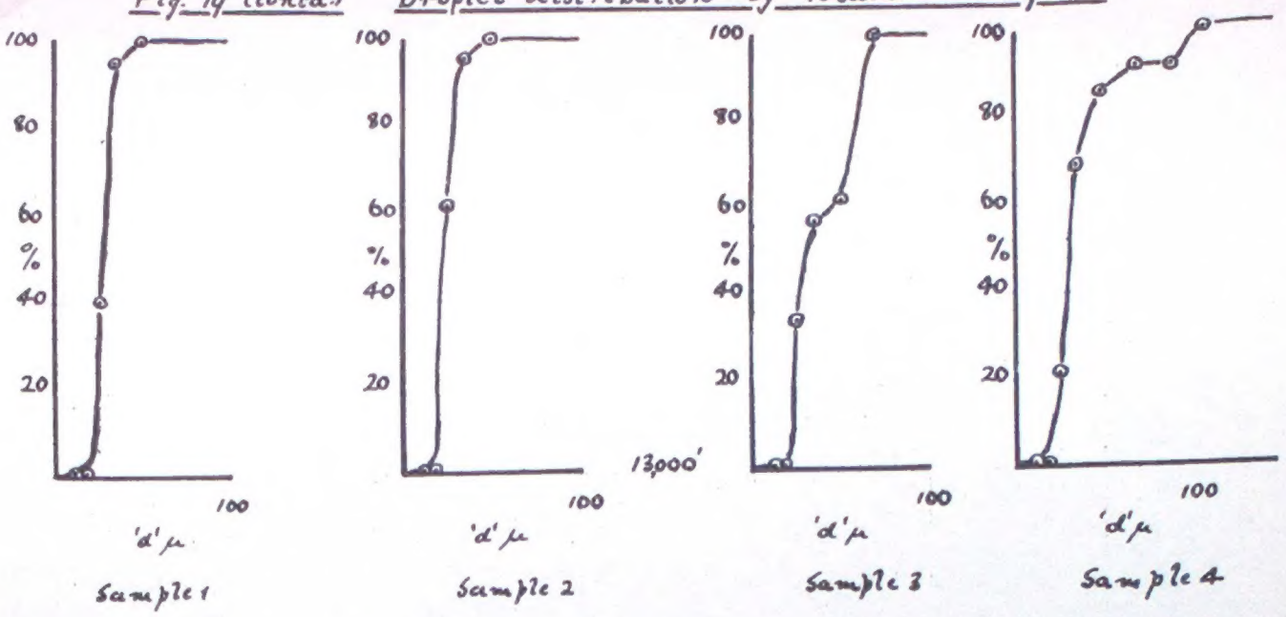


Sample 3



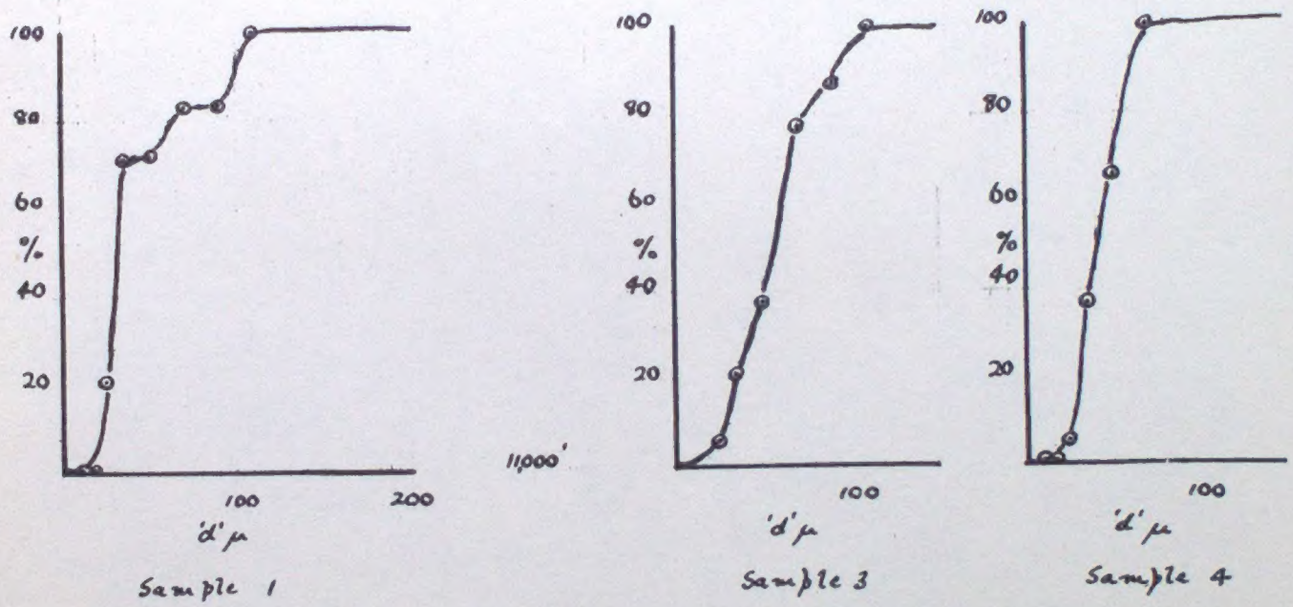
Sample 4

Fig. 19 (contd.) Droplet distribution by volume – Flight 8 M.R.P. 826

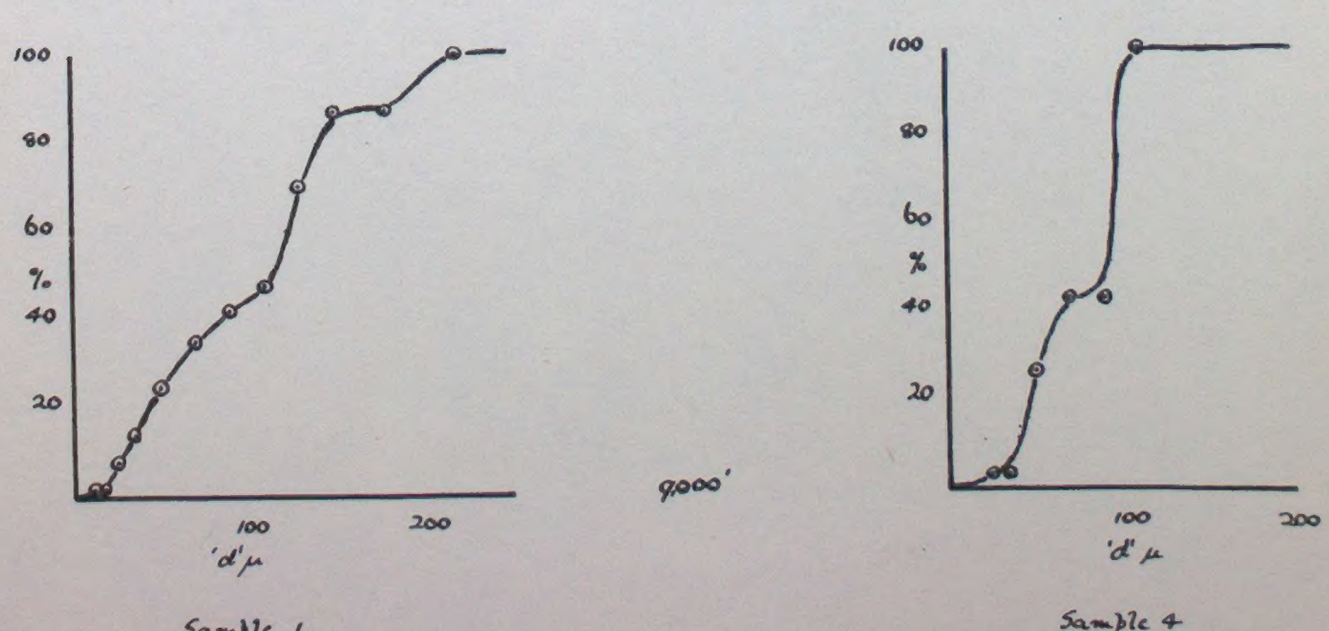


Sample 1 Sample 2 Sample 3 Sample 4

Basic sample seperation throughout 200 yd.

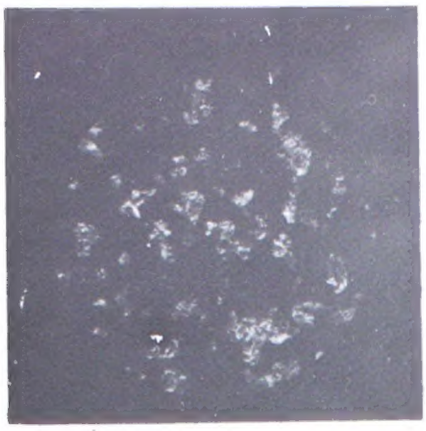


Sample 1 Sample 3 Sample 4

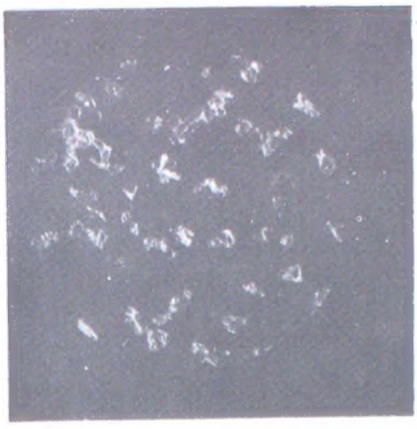


Sample 1 Sample 4

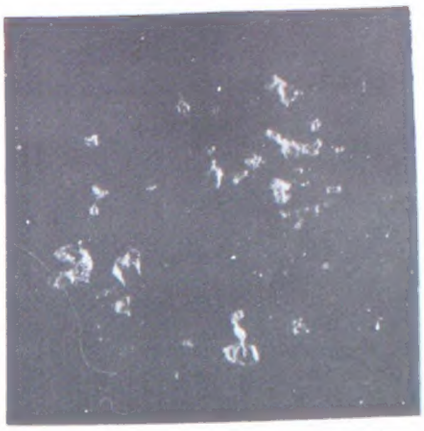
Figs. 20a-i. Typical Crystal samples



20a.

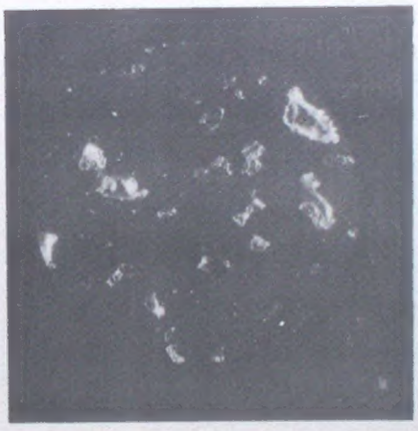


20b.

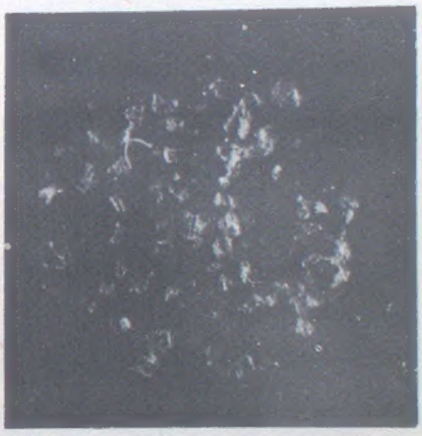


20c.

20d.

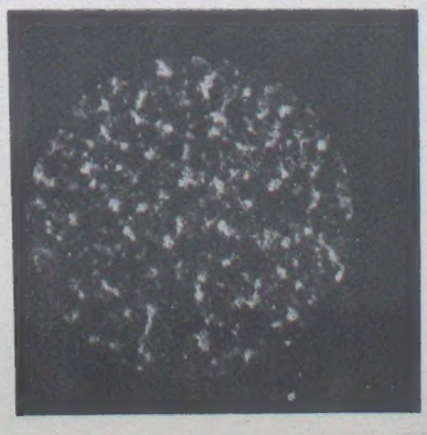


20e

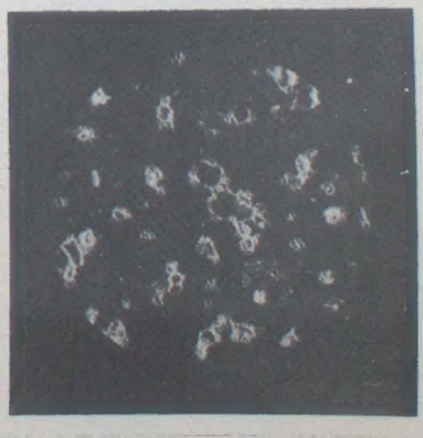


20f

20g.



20h.



20i.

M. R. P. 826